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ANALYSIS OF OPTIONS OF THE NEW ECONOMIC POLICY OF UKRAINE FOR BUILDING AN ECONOMIC POWERFUL STATE DURING THE RUSSIAN-UKRAINIAN WAR AND IN THE POST-WAR PERIOD, AS PRECONDITIONS FOR THE DEVELOPMENT OF THE DEFENSE-INDUSTRIAL COMPLEX

The article analyzes the experience of successful economic reforms and rapid economic growth in different countries of the world and proposes general approaches to building a wartime and post-war model of Ukraine's new economic policy. The authors emphasize the necessity and possibility of building a powerful defense industry only on the solid foundation of a modern, efficient and integrated national economy into global trade chains.

The article describes possible forms of cooperation between the Ukrainian defense industry and the defense industry of NATO and the EU, identifies the advantages of each of them and substantiates the need for their integrated use.

Keywords: defense industry, new economic policy of Ukraine, world experience of post-war economic growth, Marshall Plan, forms of integration of the Ukrainian defense industry with the defense industry of NATO and the EU.

INTRODUCTION

Ukraine's defense industry development strategy cannot be separated from the overall development strategy of the state, because a strong economy is the only reliable guarantee of a powerful defense industry capable of providing the Ukrainian army with the most effective weapons and military

equipment to protect Ukraine's sovereignty and territorial integrity, based on modern production technologies.

Therefore, before moving on to analyze possible ways and prospects of the Ukrainian defense industry, let us try to determine what features and properties of the Ukrainian economy will ensure the formation of an industry that can truly meet the current and strategic needs of the Defense Forces for modern weapons, military equipment and ammunition to provide a powerful response to Ukraine's aggressive neighbor.

For several years now, international and Ukrainian platforms have been discussing possible ways to rebuild Ukraine after the victory.

In the world practice, Ukraine is not the first country that needs post-war recovery and wants to build a modern and highly efficient economic model to ensure the welfare of its citizens and protect them and the territorial integrity of the state. That is why the task of analyzing and summarizing the experience of restoring countries that have suffered destruction because of military operations, building a new powerful and modern economy that should become the basis for the development of the state's defense industry is extremely relevant.

The purpose of the study is to analyze the reasons for the gradual decline of the Ukrainian defense industry since 1991 until the full-scale Russian aggression against Ukraine, to study the experience of successful post-war recovery and economic growth in countries around the world and the possibilities and ways to use it in the post-war reconstruction of the Ukrainian economy and the construction of a powerful defense industry capable of providing the Ukrainian Defense Forces with the necessary weapons and ammunition to protect the territorial integrity and independence of the state.

RESEARCH RESULTS

Analyzing the experience of post-war economic growth in countries around the world

There are many examples of post-war recovery in countries that once suffered from armed conflicts on their territory.

First of all, it is worth mentioning the experience of Germany's postwar recovery after the end of World War II. After the defeat in that war, Germany's economic situation was not the best and it suffered considerable losses. The country was divided into two geopolitical blocs – West Germany, which followed a pro-European democratic path and East Germany, which chose a totalitarian communist regime [1].

Many German cities were largely destroyed, with human losses reaching 5–7 million people. Almost every family lost relatives, often a roof over their heads and all their property. There was a shortage of coal and food. Every second person was unemployed. The economy was in a state of disrepair. About 20 % of industry was lost, production facilities were destroyed, entire plants and echelons of equipment were exported.

Ludwig Ehrhardt, Minister of Economy of West Germany (later the Federal Republic of Germany, FRG) is considered the main architect of Germany's economic success after the war [1]. Undoubtedly, U.S. assistance (under the Marshall Plan) played a role in Germany's economic deve-

lopment, but it was the reforms and rational use of funds that were decisive.

Ludwig Ehrhardt developed the fundamental principles of the «social market economy» on which the new Germany was built [1]:

- 1) development of a market economy, freedom of entrepreneurship, stimulation of investment, preservation of free competition, privatization and protection of property rights. Independence and responsibility of market participants, free choice of activities, profession, workplace, consumption, etc.;
- 2) strengthening and development of the middle class, focus on small and medium-sized businesses. The middle class, not the oligarchy, is the subject of private property;
- 3) state regulation and the active economic role of the state, whereby state regulation was understood not as state interference in economic processes, but as determining development priorities, creating «common and binding rules of the game» for all;
- 4) a balanced social policy, with the state providing assistance to those who need it;
- 5) and perhaps the most important principle without which it is difficult to implement structural changes in the state and economy is the trust of the people in the government and the chosen course. And the less social stratification in society, the greater this trust.

The funds that West Germany received from the United States, were mostly used for technical re-equipment of industries, new technologies, reconstruction and renewal of production, replacement of fixed assets, design development and science. Advanced industries were created on a new technological basis, including petrochemicals, electronics, mechanical engineering, instrumentation, electricity and optics. Export-oriented industries, such as automotive, aviation, electrical, chemical and processing, were developing dynamically and the government supported them with direct funding. The development of new technologies, investment in science, and the creation of the above-mentioned industries became the basis of the defense industry of the restored Germany. It should be noted that the transition of the entire industry to ISO standards was a key factor in ensuring high quality products not only for civilian and general industrial use, but also for the creation of advanced weapons and military equipment.

These principles and the experience of their implementation in the reconstruction of Germany are quite relevant (of course, taking into account current realities) for Ukraine.

It is also worth considering the experience of rebuilding South Korea (the Republic of Korea), whose situation after the war, which lasted from 1950 to 1953 and in which the regular armies of the United States, China and the USSR took part and where the front passed through almost all of its territory three times, was terrible. The country was virtually a complete ruin. Almost all industry remained in North Korea (DPRK). South Korea is still formally under martial law. There are still powerful fortifications and defensive positions on the 38th parallel, on the border with the DPRK. However, this has not prevented the country from making tremendous progress in economic development [2].

Today, the Republic of Korea is one of the world's largest economies and a leader in innovation, which objectively corresponds to its status as an «East Asian dragon» or «East Asian tiger». The Republic of Korea is a member of the G20, a global and regional ally of the United States and has a positive image in the international arena. The country is a global center for startups, especially given the status of Seoul, which is often called the «Asian Silicon Valley». In 2022–2024, the Republic of Korea's human development index was 0,929, which ranked it 19th in the world in this indicator. The country's nominal GDP in 2023 amounted to USD 1712.793 billion, making it the fourth largest economy in Asia and the fourteenth in the world [2].

South Korea needed not just postwar recovery, but also the development of a new postwar economy. Ukraine, too, should not only restore what it had before the war, but also move to a new level, to a new economy based on modern technology. With this in mind, it is relevant to draw historical analogies and highlight the possibilities of applying the South Korean experience to Ukraine.

South Korea has made attracting investment and new technologies a priority of its foreign and domestic policy. A number of state institutions have been created to intensify and regulate these processes. Thus, if in the early 1960s, there were only two state research institutes in the ROK: National Defense Research Institute (1953) and Atomic Energy Research Institute of the Republic of Korea (1959), a number of new research institutes and research centers were established during the 1960s and 1970s, along with the Ministry of Science and Technology (MOST) (1967). These included: The Korea Institute of Science and Technology (KIST) (1966), the Korea Advanced Institute of Science (KAIS) (1971), the Electronics and Telecommunications Research Institute (ETRI) (1976), the Teduk Science City and other research institutes. The Defense Development Agency (ADD) was responsible for the development of defense technologies. These institutions created the necessary conditions for the development of science and technology in the country as a whole and in its defense sector and provided the government with important research and advice, including in the area of policy decisions. The development of scientific research was also facilitated by significant investments, both public and private. The government, in particular, provided funding for large-scale research and development aimed at gaining competitive advantages in high-tech markets [2].

Possible recommendations for Ukraine based on the South Korean experience can be summarized as follows:

- ensuring stability of the political situation as a key factor contributing to economic growth, avoiding social and political upheavals and actively fighting corruption, which is a serious obstacle to economic development;
- ensuring that the state supports an export-oriented development model with parallel import substitution of the most critical and important products for the needs of Ukrainian citizens and national security and defense;
- achieving the competitiveness of the national economy with a focus on technology and innovation in cooperation with the United States and European countries, Japan and the Republic of Korea, in parti-

cular, in the area of cooperation/import/transfer of technology and innovation. This will allow for the development of the processing industry and investment in the production of high value-added goods instead of focusing only on the extraction and export of raw materials (including food);

- attracting foreign investment. Creation of large high-tech enterprises with the participation of foreign capital, including offset programs, to ensure the production of high-tech equipment for general industrial purposes and targeted technological complexes for the defense industry (Slogan – Build factories for the production of modern high-tech plants);
- mobilization of the Ukrainian nation around a common goal during the period of recovery and economic transformation.

In the context of taking into account the experience of the Republic of Korea, the visit of a South Korean delegation led by the Minister of Land, Infrastructure and Transport of the Republic of Korea, Won Hee Ryong, to Ukraine in September 2024 is considered very positive. Among the business representatives in the delegation were the heads of such tech giants as Samsung, Hyundai, Hanwha Solutions, Yooshin and Posco [3].

As a result of the meeting, Ukraine and the Republic of Korea agreed to develop infrastructure rehabilitation projects involving Korean high-tech experience and Korean business investment.

The experience of Turkey's economic growth may be very interesting for Ukraine. There is much to learn from Turkey. Over the past twenty years, it has built a powerful economy. According to the World Bank, Turkey's economy has been confidently ranked among the twenty largest economies in the world in recent years (18th place in 2023) [4].

The economy's rapid growth is largely due to a broad package of reforms that were implemented in the early 2000s. Its most important elements were [5]:

1) fiscal consolidation and a thorough reform of public finances, including, among other things, the harmonization of public procurement with EU standards and strengthening of auditing;

2) reducing the role of the state in the economy through privatization, which primarily included infrastructure facilities: Turkish Airlines, electricity distribution and generation enterprises (according to the World Bank, from 2002 to 2013, 12.7 billion US dollars of private investment was attracted. USD 12.7 billion of private investment in this sector was attracted from 2002 to 2013), the state monopoly in the telecommunications sector, ports, etc;

3) establishment of independent regulators in the real sector of the economy, in particular in the key sectors of energy, telecommunications and agriculture and significant increase in competition and simplification of administrative procedures for doing business;

4) cleaning up the banking system through the rapid resolution of insolvent banks (protecting depositors, not bank owners), making it impossible for «related parties» to obtain loans from their own banks and restructuring, strengthening corporate governance and partial privatization of state-owned banks;

5) granting independence to the Central Bank of Turkey, defining price stability as its main mandate and prohibiting direct financing of public debt. At the same time, its accountability to the public and transparency in decision-making were strengthened.

6) transition to inflation targeting and a floating exchange rate.

This reform package laid the foundation for macroeconomic stabilization and sustainable economic growth. The reduction of legal obstacles and macroeconomic stabilization, as well as progress in harmonizing standards with the EU, has allowed Turkey to attract significant foreign direct investment, including in privatization and to increase its participation in global supply chains.

Turkey has learned to produce high-quality high-tech weapons. It independently produces optoelectronic systems, combat drones, as well as small arms, ships and creates samples of armored vehicles and radio stations.

In addition to attracting foreign developers, the successful development of the defense industry was also ensured by the structural organization. Thus, Turkey has developed partnerships between public and private companies and higher education institutions. The companies operating in the defense industry (TAİ, Aselsan and Roketsan, Baykar, Havelsan, YONCA-ONUK, STM and others) are organized into clusters. Turkey is successfully getting rid of its dependence on foreign arms manufacturers and increasing the share of its own technologies in production. Thus, while in 2002, 62 defense projects were implemented, today there are about 700 of them. The number of companies operating in the sector has increased from 56 to 1500. Over the past twenty years, Turkey has increased its budget for its own defense projects from \$5.5 billion to \$60 billion and the industry's turnover has grown from \$1 billion to \$11 billion. Exports of the defense and aviation sectors increased from \$248 million to \$3 billion. In the field of combat aviation, Turkey started with the production of individual weapons components (General Electrics F110 engines for Lockheed Martin F-16 fighters, turbine blades for the Lockheed Martin F-35 engine, etc.). Then, F-16 fighters began to be assembled under an American license in Ankara. Then Turkey began to develop its own fighter jet, which would have a Turkish engine and weapons [6].

The design and construction of Turkey's own KAAN fighter cost Turkey \$2 billion and the first 20 fighters are planned to be delivered to the country's Air Force in 2028, with hundreds of KAAN fighters to come in the future. This was announced in May 2024 by the CEO of the aerospace company Turkish Aerospace Industries (TAI), Temel Kotil [7].

Of course, it is also possible to recall the experience of rapid economic growth and building a powerful defense industry in other countries. Their experiences and paths are very different, but they have something in common: economic freedom, entrepreneurship, protection of private property, attraction of foreign investment, innovation and sound public administration.

Using the experience of economic growth of other countries and creating a Plan for the Restoration of Ukraine

As the American economist and Nobel Prize winner Edmund Phelps noted: «Economic success depends on the

character of the nation» Edmund Phelps's very apt statement fully applies to the economic situation in Ukraine, especially after the start of Russia's full-scale aggression against Ukraine, when we are not talking about the economy, but about the very existence of Ukrainian statehood.

As the investigation by The Washington Post [8] showed, US officials were confident before and at the beginning of Russia's full-scale invasion of Ukraine that Ukraine would fall, although not as quickly as the Russians expected. But here the moral and indomitable spirit of the Ukrainian nation, which had already been clearly manifested during the Orange Revolution of 2004 and the Revolution of Dignity of 2013, came to the fore again.

Ukraine has not fallen and has been fighting for its freedom and right to life for the third year. And here again the will of Ukrainians, who in the most difficult times began to build plans for the restoration of Ukraine during the war and after the victory over the Russian aggressor, was clearly manifested.

On April 21, 2022, President of Ukraine Volodymyr Zelenskyy issued a decree on the establishment of the National Council for the Reconstruction of Ukraine from the Consequences of the War [9]. The main tasks of the National Council for the Restoration of Ukraine were defined as follows:

- development of an action plan for the post-war recovery and development of Ukraine, which, in particular, will include the restoration and development of infrastructure, housing and the military-industrial complex, structural modernization and restart of the economy, measures to overcome unemployment and support for vulnerable groups of the population;
- preparation of strategic initiatives, draft laws and regulations, the adoption and implementation of which is necessary for the effective work and recovery of Ukraine in the war and post-war periods.

Already in July 2022, the National Council for the Restoration of Ukraine presented the Ukraine Restoration Plan, aimed at accelerating sustainable economic growth, which consists of 17 National Programs in various areas of activity and is designed for the period until 2032 [10]. The National Programs include 850 projects worth more than 750 billion US dollars.

One of the first framework international documents for the recovery of Ukraine was the Recovery and Development Plan for Ukraine following the results of the international conference in Lugano on July 5–6, 2022. Subsequent conferences of this format were held in London on June 21–22, 2023 and in Berlin on June 11–12, 2024 [11].

In the expert community, discussions are underway on the choice of two main options for organizing the recovery processes in Ukraine. The first is the creation of program documents and strict adherence to them [12], the second is proposing more revolutionary measures, creative and non-standard solutions [11, 13].

Valeriy Pekar, a lecturer at the Kyiv-Mohyla Business School, believes (and the authors of the article tend to agree with him) that ensuring conditions for the massive influx of private investment into Ukraine is a prerequisite for the restoration and modernization of the Ukrainian economy,

because it was private investment that provided sufficient money to restore the economy of Western Europe, while the Marshall Plan provided 4–7 % of the necessary financing.

In his opinion, after the victory, Ukraine will face five main challenges, without the resolution of which no program will work and a large amount of investment will not come [13].

1. Long-term security. Russia is aggressive and its aggressive policy should not be expected to change. Therefore, Ukraine should be a member of NATO or have adequate security guarantees.

2. Rule of law. According to the World Justice Project (WJP), Ukraine ranked 89th out of 142 countries in the 2023 rule of law ranking, which obviously does not attract international investors who advocate for equal, transparent rules of the UAH [14].

3. Economic freedom. Ukraine ranked 130th in the world (out of 177) in the Heritage Foundation's economic freedom ranking as of January 1, 2022, with a score of 54.1, down from 56.2 in 2021 [15].

4. Demographics. In 2018–2020, there were two deaths for every one child born in Ukraine. Currently, there are three deaths per newborn citizen (of course, we must take into account the number of deaths due to Russian aggression). This ratio is one of the key indicators of the demographic crisis.

During the first half of 2024, 87,655 children were born in Ukraine, which is 9 % less than in the same period in 2023 and one and a half times less than in 2021 (87,655 children compared to 132,595) [16]. The population is aging rapidly. It is not known exactly how many Ukrainian citizens who fled Russian aggression will return from abroad, but it should be expected that the part of Ukrainians who found work and settled down will not return.

A good sign is the adoption of the Resolution of the Cabinet of Ministers of Ukraine dated September 30, 2024 No. 922-r «On Approval of the Strategy of Demographic Development of Ukraine for the Period Until 2040» [17]. Working hard to implement it is becoming one of the top priorities facing the executive branch of Ukraine to build a new economy for the state.

5. Democracy. And yet, Ukraine cannot do without external sources of funds for the implementation of these projects and other forms of assistance from international institutions and partner countries.

Marshall Plan 2.0

For several years, long before Russia's full-scale invasion of Ukraine, the issue of creating an analogue of the Marshall Plan for Ukraine, which has acquired the generally accepted name «Marshall Plan 2.0», has been under consideration [18]. First of all, we would like to emphasize that the so-called «Marshall Plan 2.0» is not (like the first Marshall Plan) a monetary fund for financing projects and activities planned by the recipient country (in this case, Ukraine).

It should be understood that the implementation of the «historical» Marshall Plan of 1947 was a very pragmatic geostrategic process and in financial terms, the Marshall Plan funds were quite insignificant. It is estimated that the aid amounted to about 3 % of the total national income of the recipient countries. Therefore, the accelerating mechanism

of the Marshall Plan through the relevant mechanisms of allocating funds was much more important.

It is important to emphasize that the Marshall Plan achieved the greatest success in countries where it was supplemented by complementary holistic national reconstruction strategies. In this context, it is worth mentioning the implementation of the concept of ordoliberalism, which was advocated by the Economic Council under the leadership of Ludwig Erhard in Germany, or the policy of «dirigism» of Charles de Gaulle in France, which, on the contrary, provided for a significant budget redistribution of funds, the creation of a system of centralized planning [18].

Both approaches worked in their time in the specific conditions of the then world economy and the characteristics of the countries receiving assistance under the Marshall Plan.

The task of Ukraine, with the help of partners, is to define and implement a balanced approach between these two extremes, directing the policy of «dirigism» precisely to define the «rules of the game», the purpose of which is to stimulate the necessary volume of private investment and technology and monitor their compliance.

Accordingly, the «Marshall Plan 2.0» should [18]:

- determine in specific areas and measures the mutual benefit of its implementation for Ukraine and European partners, Western private capital;
- guarantee the formation of a stable predictable space and the creation of comfortable conditions for the work of partners in the Ukrainian market, in particular in the implementation of recovery projects;
- provide for the formation of high-quality financial mechanisms for the precise targeting of international financial assistance resources to Ukraine for recovery;
- formulate a vision of Ukraine's promising place in the European community, including in addressing common European problems – security, demography, climate change, digital revolution, etc.;
- determine ways to implement a common European policy in Ukraine, in particular those related to the agricultural, transport, environmental, energy, regional spheres, competition, etc.;
- delineate specific areas of cooperation between Ukraine and the EU within the framework of recovery goals;
- determine areas for strengthening logistical ties between Ukraine and the EU;
- to establish priorities for technical assistance to state authorities and local governments in implementing European practices;
- to strengthen cooperation in forming institutional mechanisms for interaction between Ukraine and the EU.

A high level of intellectual technology, the intensity and efficiency of their implementation should become a criterion for the development of Ukraine's national economy and an indicator of the success of the implementation of plans.

Technological, financial and advisory assistance from partners is a necessary but not sufficient condition for rebuilding Ukraine on a new technological level. Without the persistence and stubbornness of ordinary Ukrainian citizens and its authorities, this task will remain unrealizable.

Let's move on to the second part of the article, which deals with Ukraine's defense industry.

The history of the decline of the defense-industrial complex of Ukraine

After the collapse of the former USSR, Ukraine inherited a powerful defense-industrial potential, as well as a third of all Armed Forces. In 1991, a powerful military group was located on the territory of our country (720 thousand servicemen, 6500 tanks (a fifth of which were the latest models), 7150 armored personnel carriers and infantry fighting vehicles, 3400 artillery systems, 1430 combat aircraft, 285 combat helicopters). 18 % of the defense-industrial complex of the former USSR was located on the territory of our country (3594 enterprises of the defense-industrial complex of Ukraine in 1991, which at that time employed 3 million people) [19].

Despite such a powerful inherited defense-industrial potential, it was actually not useful for ensuring the national security of the state for certain reasons, some of which can be considered as follows.

1. The influence of the Russian Federation on the policy of Ukraine as a whole and on the actions of individual politicians and its far-reaching plans to make Ukraine a satellite of Russia.

2. The influence of other countries of the world, not interested in the appearance on the map of Europe of a powerful economically and well-armed Ukraine that possesses nuclear weapons.

3. In Ukraine, there were powerful fragments of the defense-industrial complex. There was no defense industry as a system. Significant capacities for the production of finished military products had an extremely small share of closed-cycle products and were actually completely dependent on external supplies of components, materials and raw materials (primarily from Russia, especially given the huge restrictions on the supply of modern electronics from technologically advanced countries of the world). It is worth mentioning the activities of the Coordinating Committee for Multilateral Export Controls (CoCom), which exercised control over exports to the USSR and other countries of the Council for Mutual Economic Assistance during the Cold War (and later to the CIS countries, including Ukraine).

4. The weakness of the Ukrainian economy and its dependence on supplies from Russia of spare parts necessary for the repair and maintenance of Soviet-designed and manufactured weapons.

5. The requirements of international acts on arms control. The existing weapons significantly exceeded the maximum permissible for Ukraine under the Treaty on Conventional Armed Forces in Europe, signed on November 19, 1990 in Paris, which entered into force on November 9, 1992, and was later supplemented specifically for the CIS countries by the Tashkent Protocol of May 15, 1992. According to these documents, our country had significant surpluses of military equipment, accounting for about 60 % of the total amount of weapons available at that time [19].

The Budapest Memorandum, signed on December 5, 1994, turned out to be just a declaration, as it did not provide any legal guarantees for Ukraine's security, but imposed obligations only on Ukraine, which it fulfilled in good faith

by transferring nuclear weapons to Russia. This example clearly demonstrates how cautious one should be when signing such international acts. The analogies are quite obvious today. Ukraine is being massively pressured to give up its territories in exchange for promises to consider Ukraine's accession to NATO at some point.

Russia will clearly conclude that its aggression, reinforced by nuclear threats, is not met with adequate response, i.e., after a little rest and development of new weapons, Russia will start a new aggression, this time setting as a goal a special military operation to capture the remnants of Ukraine, Eastern Europe, the Baltic states, etc.

In addition, it seems that the global consequences of the fact that a state that has renounced nuclear weapons was attacked, as it is threatened with the same nuclear weapons that it handed over, are still ahead. This encourages other countries to create their own nuclear weapons to protect their independence, because it turned out that no international treaty, no international institution has any influence on an aggressor who wanted to seize someone else's territory.

The dominant force in international politics is becoming exclusively the right to force, not limited by international law. According to the authors of the article, this fact significantly increases the likelihood of a third world war. Having renounced nuclear deterrence, Ukraine began to rapidly disarm in the field of conventional weapons, choosing a course for the export of better weapons, leaving only outdated junk for itself.

The technical component of the Ukrainian army was catastrophically reduced. As the publication «Word and Deed» notes [20], only from 2004 to 2014, 2,577 tanks, 3,711 armored personnel carriers/infantry vehicles, 750 aircraft, 138 helicopters, 580 air defense systems, 734 portable anti-aircraft missile systems, 25 Tochka-U missile systems and 434 missiles (tactical and for the C-300 air defense system) were withdrawn from the Armed Forces of Ukraine.

The Temporary Investigative Commission of the Verkhovna Rada of Ukraine, established by Resolution of the Verkhovna Rada of Ukraine No. 2455-VIII of 07.06.2018, to investigate information regarding the facts of embezzlement in the Armed Forces of Ukraine and the undermining of the state's defense capability in the period from 2004 to 2017, concluded that «as a result of Ukraine's accession to the Treaty «On Conventional Armed Forces in Europe», an uncontrolled process of selling off military equipment and property of the Armed Forces of Ukraine from bases, warehouses and arsenals, selling equipment outside Ukraine, as well as the seizure, lease and sale of real estate of the former USSR Ministry of Defense began, which in turn created conditions for a gradual systemic decrease in the level of combat capability of the Armed Forces of Ukraine» [21].

The ways of disarmament of Ukraine are striking in their diversity and significant influence from the Russian Federation (sometimes overt, sometimes slightly hidden). Let us leave the corruption component of this process outside the scope of this article. We will focus on only some of them.

1. Instead of half of the Black Sea Fleet's assets, during the final distribution in 1997, Ukraine received only 18 % of its naval composition and 50 % of weapons and military equipment [21].

2. The signing on 28.05.1997 of the Agreement between Ukraine and the Russian Federation on the status and conditions of the presence of the Black Sea Fleet of the Russian Federation on the territory of Ukraine, which allowed the presence of the Russian Black Sea Fleet at the military base in the city of Sevastopol. On April 21, 2010, in Kharkiv, the Presidents of Ukraine and Russia, Viktor Yanukovich and Dmitry Medvedev, signed the so-called Kharkiv Agreements, according to which the term of the Russian Black Sea Fleet's presence in Crimea was extended for 25 years from May 28, 2017, with an automatic extension for five-year periods in the absence of a written refusal by one of the parties to the agreement. It was from this base that the Russian Federation began its invasion of Ukraine.

3. Organization of the appointment of Russian citizens to key positions in the defense sector, for example, to the position of Minister of Defense of Ukraine Dmitry Salamatin and Pavel Lebedev. D. Salamatin also distinguished himself as the General Director of the State Concern «UkrOboronProm».

4. Determination of the export of munitions and weapons as a priority area of activity of the Ukrainian defense industry. In the 90s, Ukraine was in the top ten countries in the world in terms of sales of weapons and military equipment.

5. An abnormally high number of warehouses, bases and arsenals of the Armed Forces of Ukraine that exploded during the years of independence in Ukraine. The damage caused to the country's defense capability by more than two dozen explosions is difficult to estimate, material losses are estimated at many billions of hryvnias. For example, on October 29, 2015, near the city of Svatove, Luhansk region, an explosion occurred at an artillery depot. 3.5 thousand tons of ammunition of various calibers flew into the air, including for the Smerch, Grad and Uragan multiple launch rocket systems. On September 26, 2017, ammunition was detonated on the territory of the 48th arsenal of the Ministry of Defense (Kalynivka, Vinnytsia region). At the time of the explosion, 188 thousand tons of ammunition were stored there, in particular, the Smerch, Uragan and Grad multiple launch rocket systems [22]. And so on two dozen times. Most of the conclusions of law enforcement agencies are official negligence, fires, short circuits in electrical wiring. Very convenient and timely cases for the Russian Federation.

6. The formal nature and critical underfunding of the adopted state programs for reforming and developing the defense industry. For most of Ukraine's years of independence, defense financing was carried out on a residual basis and ranged from 2.1 % of GDP in 1992 to 0.8 % in 2010. The five-year period of complete financial impoverishment of the military industry fell (and hardly by chance) in the years before the occupation of the Autonomous Republic of Crimea in 2014. The share of Ukraine's defense spending in GDP was 0.8 % in 2009, 0.97 % in 2010, 0.98 % in 2011, 1.1 % in 2012 and 1.11 % in 2013 (open data).

All these and many other reasons led to a critical loss of Ukraine's defense capabilities to protect against an aggressive neighbor.

General assessment of the current state of the defense industry in Ukraine

The situation with the financing of the defense industry began to improve gradually with the adoption by the Verkhovna Rada of Ukraine in 2018 of the Law of Ukraine «On National Security of Ukraine» [23], which, among other things, stipulated that the amount of expenditures for financing the security and defense sector should be at least 5 percent of the planned gross domestic product, of which at least 3 percent should be for financing the defense forces, but full funding for defense needs began to work only with the beginning of Russia's full-scale invasion of Ukraine and amounted to ten percent of the total. This was the main factor in the significant improvement of the situation in the Ukrainian defense industry.

The second extremely important factor was the rapid growth of national consciousness and the volunteer movement, which supplied the troops with a huge amount of personal protective equipment, drones, cars, medicines, warm clothes and much, much more.

The combination of a new level of national consciousness and a huge increase in defense funding led to the explosive growth of the private defense industry, which began to fill the gaps in the supply of the Ukrainian Defense Forces with a segment that allowed to some extent to compensate for the aggressor's huge advantage in personnel, weapons, military equipment and ammunition. During this period, this allowed for an asymmetric response, primarily due to the mass production of unmanned aerial vehicles (UAVs), electronic warfare equipment, etc.

The state concern «Ukroboronprom», having transformed into JSC «Ukrainian Defense Industry», also began to actively organize the production of munitions and ammunition, both directly at participating enterprises and in cooperation with Western defense companies.

Ukraine is gradually becoming one of the world's leading arms producers and the defense industry is developing rapidly. Thus, in the first half of 2024, domestic gunsmiths produced 25 times more ammunition for artillery and mortars than in the whole of 2022. As one of the latest examples, it can be noted that during the second International Defense Industries Forum, which took place on October 1, 2024 and was attended by representatives of about 300 companies from over 30 countries, JSC «Ukrainian Defense Industry» reached agreements on cooperation with four Western arms companies from the USA, France and Poland. This concerns interaction in the fields of ammunition and special chemicals, unmanned systems, as well as electronic reconnaissance and electronic warfare [24].

In September 2024, the Minister of Defense of Ukraine Rustem Umerov stated that today every second ammunition on the front is Ukrainian-made and in 2024 alone, the Ministry of Defense contracted drones for more than UAH 21 billion and ammunition for another UAH 9 billion, and together with the State Special Communications Service, more than a million drones were purchased for the army [25].

The situation with the production of domestic weapons and ammunition is beginning to improve, although the advantage of Russian troops in these components remains significant.

Possible directions for the development of the Ukrainian defense industry

Let's try to determine what the main promising areas are worth paying attention to when developing a new outline of the Ukrainian defense industry.

The role and place of the private component in the Ukrainian defense industry needs to be reconsidered. The experience of the war with Russia has shown that private defense companies respond more flexibly to the needs of the front. During the forum «Innovations in the Defense Industrial Complex» within the framework of the XIII International Festival of Innovation Projects «Sikorsky Challenge 2024: Innovations for Peace and Security of Ukraine», which took place in Kyiv from October 29 to November 1, 2024, representatives of private companies noted that they promptly respond to the needs of the front, comments and suggestions of the military, and the average time from receiving information about the needs to their implementation has been reduced to several months.

It is necessary to work out and ensure the implementation of a strategy for personnel renewal of employees of the defense industry enterprises of Ukraine. As was noted at the aforementioned forum «Innovations in the Defense Industrial Complex», experience shows that increasingly, success in designing the most modern models of munitions is achieved by young engineers and yesterday's students, who have an unbiased view and are armed with modern design tools and achieving a combination of their capabilities with the existing design experience of engineering workers is one of the strategic objectives.

It is important to scale up the activities of Ukrainian platforms such as Bravel and create an effective vertical management system for the implementation of innovative technological solutions in the defense sector.

An increasing number of Ukrainian and Western experts and institutions suggest paying increased attention to the opportunities that the implementation of the principle of purchasing Ukrainian weapons from Ukrainian manufacturers for the needs of the Ukrainian Defense Forces at the expense of Western partners can provide. For example, Ukraine can produce up to 4 million drones annually, of which only one and a half million are contracted in 2024 [26]. This practice can be effective and useful for both the Ukrainian defense industry and the Ukrainian Defense Forces.

Despite certain successes of both the public and private defense industries of Ukraine, it is believed that it is impossible to achieve a leapfrog increase in the production of modern (primarily complex and high-cost) weapons and military equipment for the needs of the Ukrainian Defense Forces without the direct participation of the Western defense industry in its various forms. Possible main forms of such cooperation are shown in Fig. 1.

Among these forms, one of the most acceptable is the localization of Western munitions and ammunition production on the territory of Ukraine. Among the main goals that can be achieved when implementing mass localization of Western munitions production, one can identify:

- ensuring stable supply to the Ukrainian Defense Forces of modern, high-tech, effective and proven samples of munitions and ammunition;

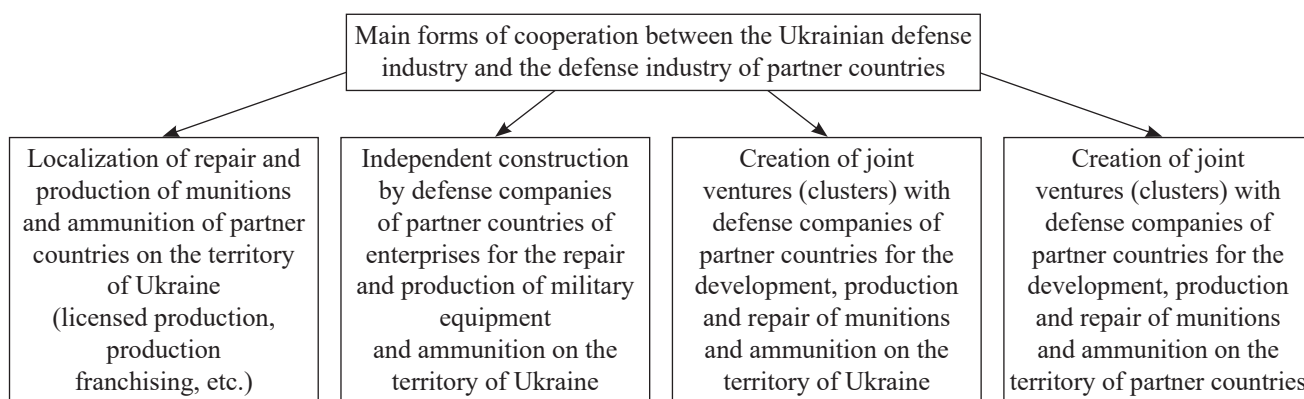


Fig. 1. Main forms of cooperation between the Ukrainian defense industry and the defense industry of partner countries

- rapid increase in the technological level of the Ukrainian defense industry through the introduction of high technologies;
- acquisition by employees of the Ukrainian defense industry of competencies in the field of high defense technologies and experience in working with them, which will be useful in the development and production of its own defense products;
- integration into the defense industry of NATO and EU countries;
- the possibility of transferring modern technologies to the civilian sectors of the state economy;
- increasing the overall technological level of Ukrainian industry, etc.

Localization can be both a part of offset schemes for the purchase of munitions and weapons and an independent process, the terms of which are discussed in the process of negotiations with leading defense companies of partner countries and be carried out in stages from large-scale and small-scale assembly to mastering the independent production of defense products from Ukrainian materials, parts and components.

Another form may be the construction of factories on the territory of Ukraine by large Western defense companies, which will remain the property of these companies, but will be worked on by Ukrainian citizens. Such an approach can even more quickly ensure an increase in the production of munitions and weapons for the needs of the Defense Forces, as well as train Ukrainian personnel to work with modern industrial technologies and influence the increase in the gross domestic product and therefore the welfare of the Ukrainian population.

A striking example of the implementation of this form can be the German arms concern Rheinmetall, which is building four plants in Ukraine, and the first of them is already operating. According to the director of the concern Armin Papperger, by the end of 2024 the first plant will already produce the first ultra-modern Lynx infantry fighting vehicle in Ukraine, adding that the company owns 51 % of the shares of this enterprise. Papperger also noted that Rheinmetall is on the way to building a gunpowder plant, an ammunition manufacturing plant in Ukraine and also plans to establish the production of air defense systems [27].

Another effective form of increasing the production of munitions and establishing strong ties with the defense

industry of partner countries is the creation of joint weapons production (including in the form of clusters as a modern form of quasi-integration associations). The prospects for the creation of joint Ukrainian-French production in our country were announced by the President of Ukraine Volodymyr Zelensky on October 12, 2024. The main advantage of such a form is, of course, the integration of Ukrainian defense industry enterprises into the European defense industry [28].

The introduction of another form of cooperation between Western and Ukrainian defense enterprises was announced by the Minister of Economy of Lithuania Aushrini Armonaitė. She reported that a Ukrainian company will begin construction of a new generation explosives plant in Lithuania in 2025 and added that as a result, the defense potential of Ukraine and Europe will grow, both in terms of weapons and ammunition and in terms of advanced defense and security technologies. Certainly, the key advantage of this form of cooperation is the ability to ensure the safety of ammunition production from bombings and missile attacks [29].

As reported on the platform «Informative Resistance» [30], the defense company Summa Defense is opening a drone production plant in Finland, which will be carried out jointly with Ukrainian partners. The purpose of opening a new enterprise is to quickly increase the production capacity of drones used in combat operations in Ukraine. «The drones will be supplied not only to Ukraine, but also to the countries of the European Union and NATO», said the executive director of Summa Defense Jussi Holopainen.

For the systematic and targeted use of internal budget resources, resources of assistance from partner states and others to create advanced defense technologies and scientific research in the field of high-tech weapons, it is advisable to consider the issue of creating a «Fund for Defense Technologies and Scientific Research in the Field of High-Tech Weapons» [31].

The strategic goals of the Fund's work should be:

- ensuring a change in the level of defense industry technologies from the post-Soviet level to the level of technologies of advanced countries;
- developing and implementing in the practice of building the defense industry of Ukraine criteria-based approaches to choosing priority technologies of the present and the future;
- ensuring scientific research in breakthrough areas of creating weapons and advanced technologies;

- creating a system of checks and balances to minimize corruption risks when financing projects and programs from the Fund.

The sources of financial resources of the Fund should be:

- funds from international financial assistance resources;
- funds from the alienation of illegally obtained material and financial resources;
- part of funds from the assets of the Russian Federation to compensate for the damage caused by the robbery and destruction of the Ukrainian defense industry during the war (reparations);
- budget funds;
- voluntary (charitable) contributions from organizations and individuals – citizens of Ukraine and foreigners.

The fund should include a Supervisory Board, a Scientific and Technical Council and a full-time expert group to select specific works and the main topics of breakthrough research areas. For interdepartmental coordination, it is considered appropriate to restore the position of Vice Prime Minister for Defense Industry.

The implementation of all these and many other projects should be a guarantee of the growth of the industrial and defense capabilities of Ukraine, its Defense Forces, to ensure the repulsion of Russian aggression.

CONCLUSIONS

Based on the results of the analysis of the experience of successful post-war recovery and construction of the economy of different countries of the world and at different times based on the latest technologies, general approaches to building a model of a new economic policy of Ukraine and the creation of a powerful defense-industrial complex of the state are proposed.

It is noted that one cannot neglect the opportunities that can be given to Ukraine by using the approaches tested by other countries, but modernized, to build a new, strong economically and politically successful state. The conclusion is made about the need to use all possible forms of cooperation with the defense industry of NATO and EU countries to build a powerful, modern Ukrainian defense-industrial complex, capable of providing the Defense Forces of Ukraine with highly effective weapons and military equipment. The authors also express confidence that a powerful defense industry can be built only on a solid foundation of a modern, effective and integrated into global trade chains of the national economy.

In the next article on this topic, the authors plan to investigate in detail the economic mechanisms of dependence and influence of the national economy on building the capabilities of the defense-industrial complex, aimed at providing the Defense Forces of Ukraine with modern and highly effective weapons and military equipment.

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**АНАЛІЗ ВАРІАНТІВ
НОВОЇ ЕКОНОМІЧНОЇ ПОЛІТИКИ УКРАЇНИ
ДЛЯ ПОБУДОВИ ЕКОНОМІЧНО ПОТУЖНОЇ
ДЕРЖАВИ
ПІД ЧАС РОСІЙСЬКО-УКРАЇНСЬКОЇ ВІЙНИ
ТА У ПОВОЄННИЙ ПЕРІОД,
ЯК ПЕРЕДУМОВИ ДЛЯ РОЗВИТКУ
ОБОРОННО-ПРОМИСЛОВОГО КОМПЛЕКСУ**

У статті проведено аналіз досвіду успішного проведення економічних реформ та забезпечення стрімкого зростання економіки різних країн світу, запропоновані загальні підходи до побудови повоєнної моделі нової економічної політики України та побудови, ґрунтуючись на можливостях економіки, потужного оборонно-промислового комплексу (ОПК) держави, здатного забезпечити потреби Сил оборони України у сучасному і високоефективному озброєнні та військовій техніці (ОВТ) і боєприпасах.

Зроблено висновки, що саме забезпечення умов для масового надходження приватних інвестицій в Україну є головною передумовою для відновлення та модернізації економіки України.

Вказується, що незважаючи на успішний розвиток останнім часом як державної, так і приватної оборонної промисловості України, досягнути стрибкоподібного нарощування виробництва сучасних (передусім складних і велико вартісних) зразків ОВТ для потреб Сил оборони України неможливо без безпосередньої участі західної оборонної промисловості у її різноманітних формах. Наведена характеристика можливих форм співпраці українського ОПК та оборонної промисловості НАТО та ЄС, визначені переваги кожної з них.

З метою забезпечення системного і цільового використання внутрішніх бюджетних ресурсів, ресурсів допомоги держав-партнерів та інших джерел для створення передових оборонних технологій та наукових досліджень у сфері високотехнологічного озброєння запропоновано розглянути питання створення Фонду оборонних технологій та наукових досліджень у сфері високотехнологічного озброєння.

Вказується на необхідність та можливість побудови потужного ОПК лише на міцному підґрунті сучасної, ефективної та інтегрованої у світові торгові ланцюжки національної економіки.

Ключові слова: оборонно-промисловий комплекс, нова економічна політика України, світовий досвід повоєнного економічного зростання, план Маршала, форми інтеграції українського ОПК з оборонною промисловістю НАТО та ЄС.

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THE APPROACHES TO STRATEGIC MANAGEMENT OF DEFENSE RESOURCES: THE US EXPERIENCE

The article argues that for effective management of defense resources, it is necessary to coordinate strategic priorities with the general system of defense resource management and public finances. Attention is focused on the fact that in the USA several levels of such coordination are distinguished: the initial, level of direct regulation and control, the level of structural regulation and efficiency assessment. It is revealed that the process of reforming public finance management in the USA faces a number of problems, in particular, coordination of goals, responsible parties, adjustment of the public finance management process itself and, if necessary, its alignment. Therefore, it is the defense strategy and action planning that allows achieving the desired results. The article examines that it is strategic resource management that makes it possible to form a plan to achieve goals, ensure comparison of goals and desired results, assess all priorities and risks and also establish responsibility. Regarding defense planning, it is noted that it is important to bridge the gap between resources and planners who develop a joint strategy for the future capabilities of the armed forces and state financial authorities, which should allow translating this plan into reality. Enhanced coordination of relationships and different views on resource provision processes is possible through decentralization, i.e. the transfer of some powers (authorities) to lower organizational levels, in particular by fiscal and administrative methods. The main areas of improvement of strategic resource provision are identified, among which the following can be distinguished: development of better models for: assessment and management of risks, design of necessary capabilities / results to support them, assessment of necessary input resources and their cost and measurement of the effectiveness of results. In addition, attention is

focused on what needs to be continued or improved: search for the most effective ways (cost of input resources used to produce a finished ship) to provide capabilities, monitoring of productivity, flexibility of «solutions», connection of data and systems to provide information.

Keywords: management of defense resources, strategic priorities, public finance resources.

INTRODUCTION

The international system frames the forces and trends in the global environment; it also frames the workspace of national security policy and strategy makers. As they work through the formulation process, with an understanding for the interests and objectives of any actors in a given situation, those involved in the business of policy and strategy making must be able to account for the associated state and nonstate actors present in the international system. In addition, it has become particularly important that they be able to assess the competing values associated with the global actors, both state and nonstate, especially in relation to the Global War on Terror. Also, given the criticality of being able to call upon other nation states and international or multinational organizations for support, the strategist or policymaker must know which alliances and coalitions are stakeholders in the issue in question. The international system also affords the strategy or policymaker numerous opportunities for advantage. If a nation-state can come to the assistance of another nation-state or region in time of need like a natural disaster or failing economy, the opportunity exists to demonstrate concern and ultimately gain some level of influence with the entity in need. The same may be true when cooperating with other states as they transition toward democratic forms of government or market economies, or when accepting an international regime like an arms control treaty. In all cases, these are opportunities to gain acceptance and influence through and with other actors in the international system.

RESEARCH RESULTS

For effective management of defense resources, it is first necessary to align strategic priorities with public finance management [4]. In the USA, several levels of such coordination are distinguished: initial, regulation and control, structured discipline and efficiency and Effectiveness (aspirational). Let's consider each of them in more detail.

Level 0: Opaque, Unreliable, Unaccountable characterized by:

- no transparency to decision making;
- limited accountability for public funds;
- no or limited audit of expenditures;
- plans and budgets are of poor quality;
- budget is informal and unreliable.

Level 1: Regulation and Control is being evaluated:

- focus is on regulation and control of expenditures;
- disciplined and reliable expenditure information due to increased accountability and transparency;
- little attention to the quality of expenditures;
- budget is formal and reliable but lacks strategic focus.

Level 2: Structured Discipline based on:

- focus on improving links between strategic plans and public expenditures;

- mixture of ex-ante and ex-post controls on use of public resources;
- introduction of multi-year focus and separation of operating and capital budgets;
- internal controls, audit and monitoring mechanisms in place but centralized;
- budget is formal, reliable, multi-year and strategic plans influence the allocation of some resources.

Level 3: Efficiency and Effectiveness (aspirational) characterized by:

- focus on improving performance of spending units;
- budget users accountable for impact on outcomes through contracting with central ministries;
- multi-year budgets reflecting strategic plans are classified by program;
- accounting and reporting on modified accrual basis with strong focus on transparency;
- budget is formal, reliable, multi-year and strategic in focus with performance information influencing the future allocation of resources.

It is worth noting that the process of reforming public financial management in the United States is not as complicated as it seems. However, it faces a number of problems such as goal alignment, role alignment, alignment and different, perspectives on processes and terms, system or process alignment [2]. Defense strategy and planning: to guide action that will help achieve desired outcomes. In addition, it enables: provide plans to achieve goals, provide cascading and measurable goals (desired outcomes), create a method for knowing priorities and making risk/tradeoff decisions, create an accountability framework.

Regarding the US Public Financial Management System (PFMS), it makes it possible to control the distribution of all resources in particular:

1. Support all financial operations.
2. Collect accurate, timely, complete, reliable and consistent information on public financial events.
3. Provide adequate management reporting.

4. Support government-wide and agency policy decisions.

5. Produce auditable financial statements [3].

Let's take a closer look at Role Alignment. One of the great difficulties in defense planning and resources is bridging the divide between planners who develop a joint strategy for the current and future capabilities of the armed forces and the budgeters who must translate this plan into actual inputs purchased [1]. Alignment and different perspectives on resourcing processes and terms are shown on Fig. 1.

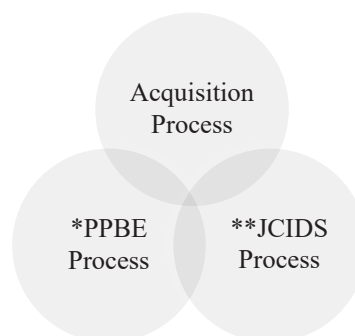


Fig. 1. Alignment and different perspectives on resourcing processes and terms

* PPBE – Planning, Programming, Budgeting and Execution;
 ** JCIDS – Joint Capabilities Integration and Development System

Extended interconnection alignment and different perspectives on resourcing processes and terms are shown on Fig. 2.

Expanded coordination of relationships and different views on resource provision processes is possible through decentralization, i.e. devolution of some authorities (powers) to lower organizational levels:

- Fiscal: more fiscal decision-making authority and economic resources.

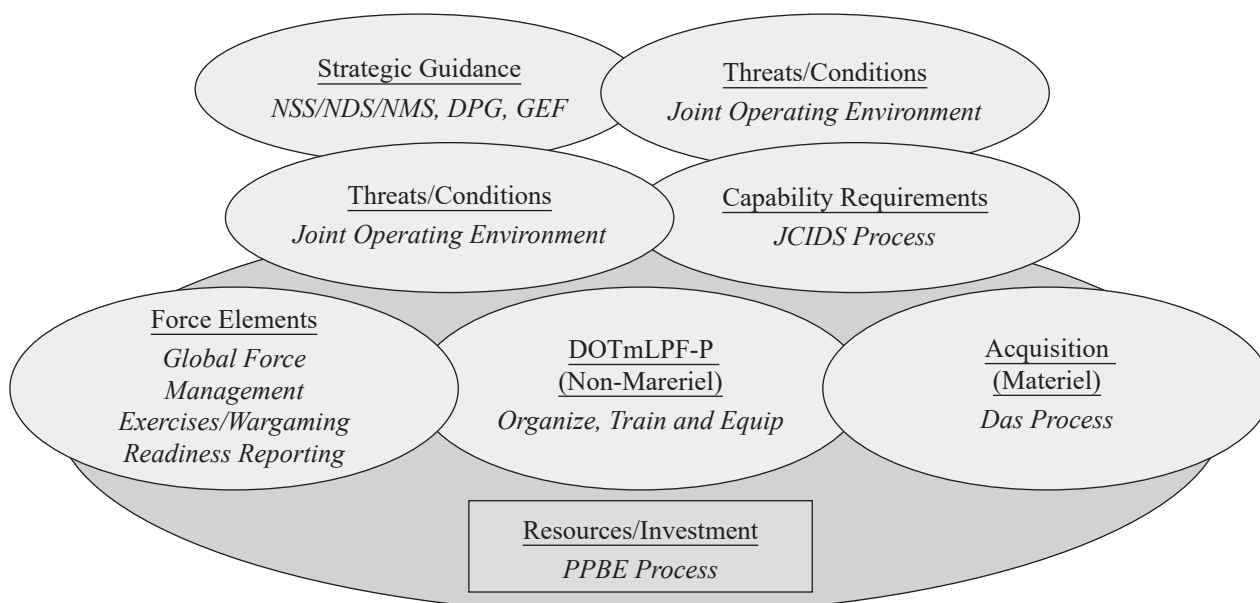


Fig. 2. Extended interconnection alignment and different perspectives on resourcing processes and terms

- Administrative: more administrative decision-making authority [5].

Effects of centralized or decentralized decision authority will show in the Table 1.

Table 1. Effects of centralized or decentralized decision authority

Centralization	Decentralization
Decisions made at senior level, which has authority to direct major change	Decisions often made by personnel closest to situation
Decisions consistent with strategic objectives	Engages personnel and promotes initiatives
Can reduce duplication of activities and risk of making wrong decisions at lower levels	May enable more flexible response to rapid environmental change
May be more consistent in terms of dealing with all stakeholders	Promotes better accountability
Discourages initiative among personnel	Puts organization at risk for bad decision making and favoritism

In the early development of PPBS, one of several (arguably) critical opportunities may have been missed:

- The Office of the Secretary of Defense (OSD) did not change the existing budgetary system, which allowed the military departments largely to retain their budgetary independence.
- The military departments had to adopt similar processes and structures to feed into new OSD processes, but they were able to protect their respective identities, preferred weapons systems and relevance.

Alignment is achieved through: planning, management and control of the resource system in government, namely:

1. Planning, programming and budgeting (PPB, PPBS, PPBES, PPBEAS, etc.).
2. Program budgeting.
3. Management by objectives (MBO).
4. Zero-based budgeting (ZBB).
5. Target-based budgeting.
6. Management information systems.
7. Performance measurement, reporting and monitoring.
8. Balanced Scorecard.
9. Quality circles (extended to Baldrige, etc.).
10. Performance-based budgeting.
11. Output budgeting.
12. Total quality management/leadership (TQM/TQL).
13. Program analysis (prior to program approval).
14. Program evaluation (after program approval).
15. Forward year projection of expenditures and revenues.
16. Results-based leadership (results-based budgets, outcome-based budgets).
17. Values-based leadership.
18. Capabilities-based planning (not a resources management system) [6].

For public sector organizations, there is often a drive to adapt tools, techniques, processes, systems, etc., from the private sector in a quest to meet strategic goals and improve efficiency without first asking whether they will

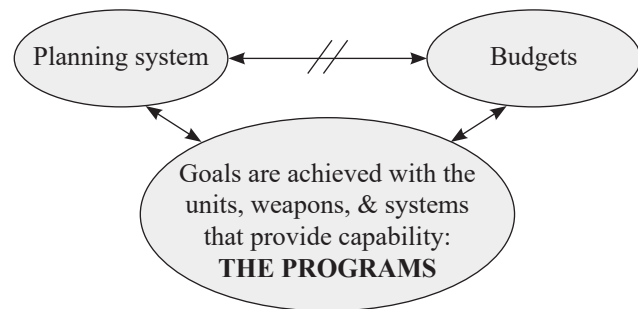
help the organization achieve its strategic goals or manage resources better.

The main recommendations are:

- Supports resource allocation activities and processes to best achieve strategy.
- Documents and justifies programs to our governments for appropriating.

Linking Planning to Budgets are shown on Fig. 3.

Analysis and decision-making will always depend on a concrete appreciation for the way capabilities are instantiated by programs (Fig. 4).



Linking Planning to Budgets
Threats ↔ Strategies ↔ Forces ↔ Budget
Fig. 3. Alignment and different perspectives on resourcing processes and terms



Fig. 4. FYDP Structure

Five Elements of a PPB-Type System:

1. A program structure – a classification of the courses of action open to an organization for attaining its objectives.
2. An approved program document that includes precise, quantitative data on needs, resource inputs and program outputs extending a number of years into the future.

3. A decisionmaking process that establishes the functions, rules and timetables for the actions required by the system.

4. An analysis process for measuring effectiveness and for weighing alternatives.

5. An information system that supplies the data required to implement the system.

PPB-type system includes such kinds of issues:

1. Added bureaucracy.
2. Organizational «mistakes» or issues.
3. Allocating «fairly».
4. Inertia.
5. Politics.

CONCLUSION

There is a growing view that American foreign policy has tended to be more assertively unilateral in recent years. America's refusal to join the international ban on antipersonnel land mines, its rejections of the Kyoto treaty on global warming, an inspection and verification protocol for the Biological Weapons Convention and its withdrawal from the International Criminal Court and the Anti-Ballistic Missile Treaty are offered as evidence of a policy of avoiding international commitments that might constrain America's freedom of action. Critics argue that the United States pursues its own international agenda without regard for the interests, views or concerns of the rest of the world. The response is that the United States is acting, as all states should and must, in its own self-interests. The main areas of improvement strategic resourcing are develop better models to: assess and manage risks, project needed capabilities/outputs to support them, estimate inputs needed and their costs and measure effectiveness of the outputs. Also need continue or improve: finding most efficient ways (cost of inputs used to produce the output of a ready ship) to provide capability, monitoring performance, flexibility in «solutions», connect data and systems to provide information.

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ПІДХОДИ ДО СТРАТЕГІЧНОГО УПРАВЛІННЯ ОБОРОННИМИ РЕСУРСАМИ: ДОСВІД США

У статті обґрунтовано, що для ефективного здійснення управління оборонними ресурсами потрібно узгоджувати стратегічні пріоритети із загальною системою управління оборонними ресурсами та державними фінансами. Акцентовано увагу на тому, що в США виокремлюють декілька рівнів такого узгодження: початковий, рівень безпосереднього регулювання і контролю, рівень структурного регулювання та оцінки ефективності. Виявлено, що процес реформування управління державними фінансами в США стикається з низкою проблем, зокрема узгодження цілей, відповідальних виконавців, налагодження самого процесу управління державними фінансами та у разі необхідності його вирівнювання. Тому саме стратегія оборони та планування дій дозволяє досягти бажаних результатів. В статті досліджено, що саме стратегічне управління ресурсами дає можливість сформувати план досягнення цілей, забезпечити порівняння цілей та бажаних результатів, оцінити всі пріоритети та ризики, а також закріпити відповідальність. Щодо оборонного планування зазначено, що важливо подолати розрив між ресурсами, що виділяються, проєктувальниками, які розробляють спільну стратегію для майбутніх можливостей збройних сил та державними фінансовими органами, які повинні дозволити перевести цей план в реальність. Розширене узгодження взаємозв'язків і різні погляди на процеси ресурсного забезпечення можливі шляхом проведення децентралізації, тобто передачі деяких повноважень на нижчі організаційні рівні з використанням фіскальних та адміністративних інструментів. Виокремлено основні напрями вдосконалення стратегічного ресурсного забезпечення, серед яких можна виділити: розробку кращих моделей для оцінки та управління ризиками, проєктування необхідних можливостей / результатів для їх підтримки, оцінки необхідних вхідних ресурсів та їх вартості та вимірювання ефективності результатів.

Ключові слова: управління оборонними ресурсами, стратегічні пріоритети, оборонне планування, державні фінансові ресурси.

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CONCEPTUAL AND METHODOLOGICAL ASPECTS OF MANAGEMENT OF THE DEVELOPMENT PROCESS OF THE ARMS SYSTEM OF THE STATE'S ARMED FORCES WITH DYNAMIC CHANGES IN EXTERNAL AND INTERNAL FACTORS IN CONDITIONS OF UNCERTAINTY OF THE SITUATION AND THE MANIFESTATION OF RISK FACTORS

The article considers the basic provisions of managing the development of the state's armed forces' armament system in modern conditions at the conceptual and methodological level. It is proposed to use a management technology that combines methods of program-targeted planning of the development of weapons and military equipment (WME) and methods of situational analysis in the process of implementing programs for this development in the presence of factors of uncertainty and the manifestation of risk signs.

Keywords: *problem situation, uncertainty and risk factors, situational analysis, situational task, resource reserve, automated control technology, control system.*

INTRODUCTION

The potential capabilities of the armed forces of a state to perform their tasks are largely determined by the level of their technical equipment, which is embodied in the weapons system as the material and technical basis for the

combat power of the armed forces and support of troops (forces) in a combat-ready and combat-capable state.

As it is known [1], the armament system of the armed forces can be considered as a reasonably organized, subordinate to their tasks and structure set of mutually agreed and complementary in terms of functions and combat (functional) capabilities of samples (complexes, systems) of weapons and military equipment of various types and purposes (combat vehicles, combat control equipment, combat and logistical support) designed to provide technical support for the effective conduct of operations (combat actions) by armed forces (groups of troops, forces) under a unified command and operational control in wartime and to perform their tasks in the context of daily activities, peacekeeping and other operations.

Thus, the armament system of the armed forces can be considered as a unified complex dynamic organizational and technical system of defense purpose, which is focused on ensuring the effective performance of tasks by the armed forces, and which is the object of management in the process of its development.

Substantiation of the concept of development of the state armed forces weapons system in the program period and in a somewhat longer perspective, operational and strategic, tactical and system technical requirements for it and its structural components, as well as shaping and determining its parameters are key tasks that are solved in the period before the program-targeted planning of the development of WME, preparation of the draft of the relevant state target program aimed at ensuring the fulfillment of the tasks of comprehensive technical equipment armed forces.

Solving the problem of acquiring defense products to re-equip the armed forces with new and advanced models of weapons and military equipment is currently one of the priority areas of activity in the military-technical sector of the defense sector [2].

This necessitates the urgent implementation of balanced, more effective and purposeful activities and works supported by the organizational structures of state and military administration in the program-targeted planning of the development and acquisition of WME for the comprehensive and sustainable equipping of the armed forces in the program period and in a somewhat longer perspective when signs of uncertainty in the internal and external situation and risk factors appear.

The object of consideration and management in this case should be the process of sustainable formation, placement and execution of orders, procurement and supply of combat and support equipment necessary for state defense needs. The key principle of building such a system of activities should be the principle of integration (unity), which implies the use of the feature of balanced integration of activities and works in managing the development of complex technical systems for military purposes. Such a requirement can be effective in the conditions of stable manifestation of geopolitical, military-strategic, scientific, technical, economic and other forecast factors of the expected external situation over time.

The classical methodology of program-targeted planning (PTP) is quite effective in conditions of predictability and

stability of the internal and external situation, when long-term forecasts are possible, containing the necessary initial data for quantitative research in the presence of reliable operational and strategic scenarios with the necessary levels of solving the main tasks of implementing programs and plans for the development of weapons and military equipment.

In today's conditions, this requirement turns out to be very difficult to fulfill or even, in some situations, practically impossible. The main reason for this is the instability and volatility of geopolitical, military, economic, social and other conditions, the expansion of the range of uncertainty and risk factors, the growing dynamics of change and the nonlinear nature of the processes taking place. As a result, there is incompleteness, inaccuracy, fragmentation and contradictions in the technical and economic input data used in planning.

As a result, these circumstances lead to relatively low reliability of forecasts of the conditions for the implementation of programs for the development of the WME and to decrease in the sustainability of the planning documents being formed, even in the short term.

Thus, it can be argued that there is a contradiction in practice between the depth of reliable forecasts of macro indicators of programs for the development of WME and the conditions for their implementation, which are set by the planning time interval in accordance with the requirements of the legislation governing the process of classical planning and management of WME development.

This was the objective reason for finding new ways to solve it and improve the efficiency of managing the development of WME in general. At the same time, WME development management remains an integral part of capacity development programming [3] and it is considered expedient to preserve all the main methodological components and principles of the program-targeted approach to solving WME development problems (planning from needs to tasks, end-to-end planning for the entire life cycle

of WME samples, planning from tasks to resources, the criterion «effect – resource costs», program slippage in time, etc. [2], supplementing them with software and tools within the WME development management system, adequate to the new conditions of activity in the military-technical sector of the defense industry.

The question arises as to what these tools should be in order to obtain the desired positive effect from their application. However, the principles of the PPP contribute to the purposefulness, reality, expediency and adaptability of plans to the fullest extent only in conditions of internal and external stability of the situation, but do not provide a sufficiently tangible positive effect in the real and rapidly changing conditions of today, although their use in managing the development of WME should not be completely rejected.

The purpose of the article is to substantiate the need (expediency) of introducing a situational approach to the process of managing the implementation of WME development programs in the presence of uncertainty and risk factors and to determine its role and place in preventing the development and solving emerging problem situations.

RESEARCH RESULTS

Planning for the development of weapons and military equipment is a system of measures, works and targeted actions to develop programs and plans for achieving certain capabilities [3], focused on the coordinated development of the weapons system in terms of goals, resources, time and technical direction and ensuring the required level of comprehensive technical equipment of the armed forces in accordance with their tasks.

The main stages of strategic planning for the development of weapons and military equipment are shown in Fig. 1.

The WME development management system, like any management system, includes a managed subsystem (management object) and a control subsystem (management object, management subject) (Fig. 2) [4].

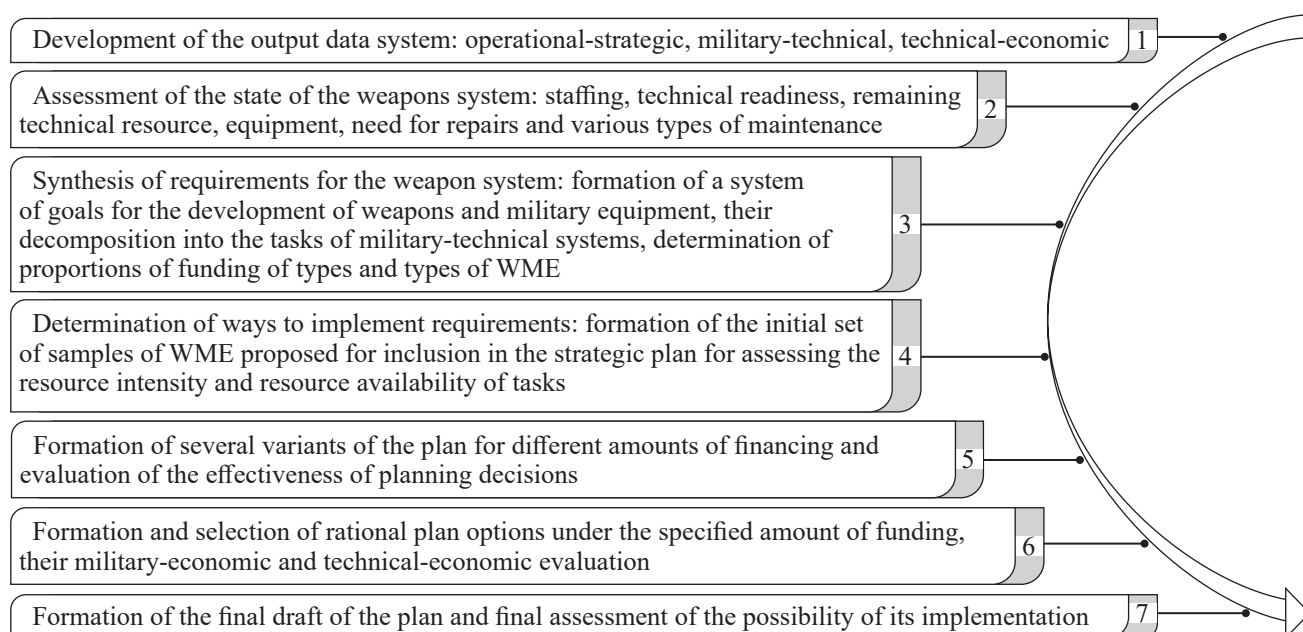


Fig. 1. Stages of strategic planning of WME development

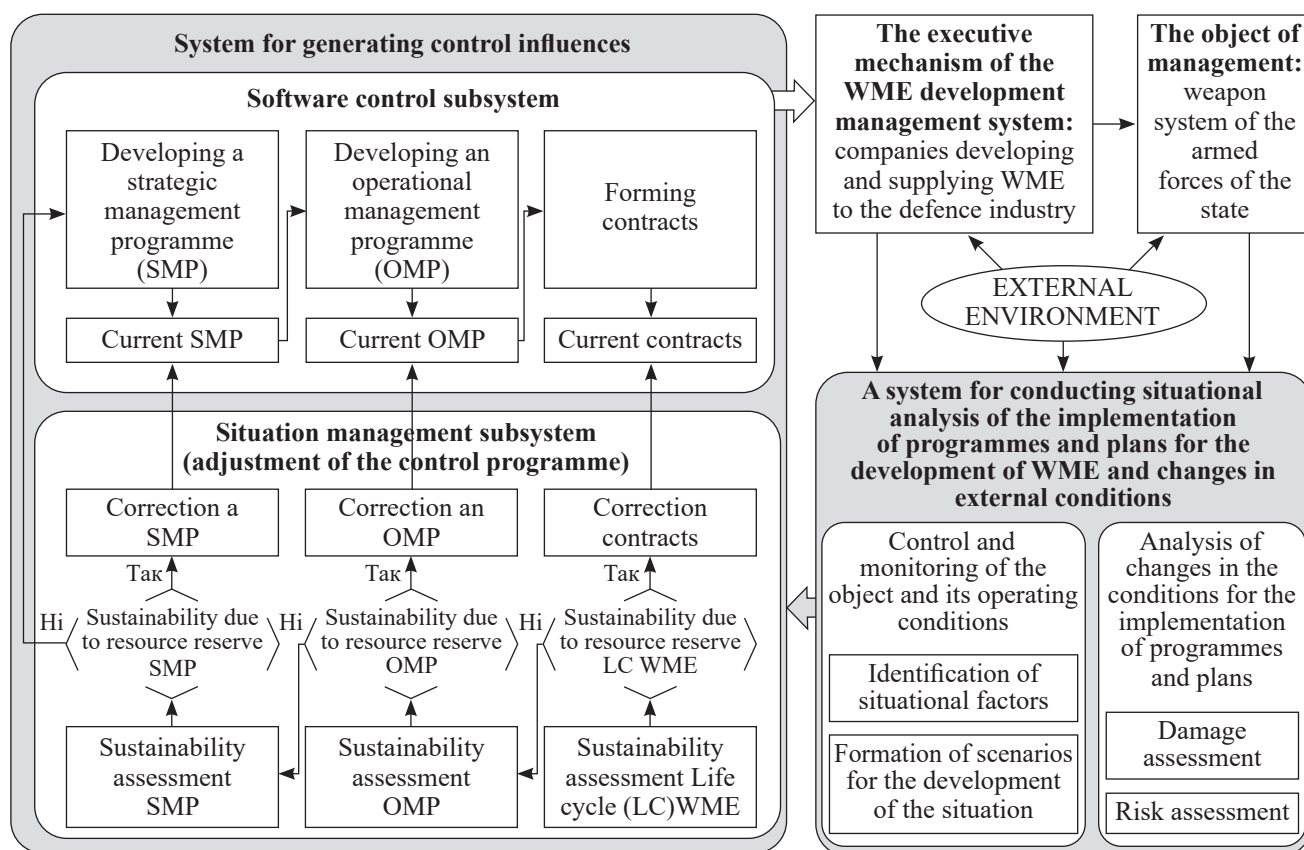


Fig. 2. Scheme of program and situational management of WME development

The above-mentioned contradiction in the practice of managing the development of WME can be achieved by supplementing the existing methods of solving management problems based on situational analysis to ensure timely resolution of problem situations in the process of implementing programs for the development of WME and supplementing program management with situational elements that provide information, organizational and technological capabilities to solve a set of emerging problem situations [5]. At the same time, the main methodological components and principles of the program-targeted approach to solving the problems of WME development should be preserved.

When substantiating and formulating WME development plans, various types of risks that may arise in the process of their implementation should be investigated and, accordingly, the development of planning documents should be based on the mandatory consideration of uncertainty and risk factors.

At the same time, in order to effectively manage the development of weapons and military equipment in modern conditions, it is necessary to carry out:

- continuous control and monitoring of changes in the level of a particular type of risk;
- analysis and synthesis of different scenarios of a particular situation and assessment of its impact on the state of all objects involved in the process of WME development;
- assessment of potential alternative opportunities to prevent negative changes in the situation;
- formulating a real-time solution to the problem situation that will minimize possible damage.

The qualitative solution of these tasks clearly requires the use of scientifically based methods and models of situational analysis and the application of advanced information technologies for data processing.

Based on the above provisions, we can conclude that there is a contradiction between practice and theory, which is the objective need for situational analysis in the process of implementing programs for the development of weapons and military equipment and the lack of appropriate methodological and technological support.

The contradictions in practice and between practice and theory indicate the relevance and necessity of solving the scientific problem, which is to develop methods for conducting situational analysis and solving problem situations for the purpose of reasoned solution of situational tasks in the process of implementing programs for the development of weapons and military equipment. Within the framework of this problem, the object of research is the technology of managing the process of WME development – a set of scientifically based methods and techniques for processing management information in order to make and implement management decisions, ordered by the time of execution.

The subject of the study is the methods of analysis, forecasting and solving problem situations in the process of implementing programs for the development of weapons and military equipment.

At the same time, the purpose of the research may be to increase the validity and efficiency of decision-making on solving problem situations in solving situational tasks in the process of implementing programs for the development

of weapons and military equipment based on situational analysis.

As a means of achieving this goal, the concept of situational analysis can be proposed and used for this purpose, which consists in:

- continuous control and monitoring of the dynamics of changes in the current situation, disclosure of patterns and trends in its development;
- timely identification of risk factors that cause problematic situations and a combination of events that increase the risk of their realization and development;
- synthesizing and analyzing alternative scenarios of the situation development (including problematic situations that have already occurred) as a result of the risk factors implementation;
- assessing the potential danger of a problematic situation for each risk factor and their various combinations, as well as possible damage as a result of its occurrence and development;
- identification of preventive management decisions under various scenarios of changes in the situation to prevent its occurrence and negative development (loss prevention);
- formulating management decisions to address an existing problem situation (minimizing damage).

In the development management system, it is necessary to implement a comprehensive information technology – a

regulated information process that determines the procedure for information circulation, its transformation, analysis and decision-making. When substantiating proposals for the annual plan for procurement of goods, works and services for defense purposes, it is necessary to form a set of plan options that best meet the intention of achieving medium-term and long-term goals and that provide different values of aggregate indicators for different projected amounts of allocations.

A rational version of the annual procurement plan for defense goods, works and services (Fig. 3) should be developed based on the results of the forecast and analysis of the consequences of its implementation and the nature of its impact on the state of the armed forces' weapons system and the defense industry.

In the process of implementing the developed planning documents, deviations from the planned results inevitably occur due to unforeseen influences. Therefore, when these deviations occur, it is necessary to make prompt decisions on their elimination (reduction). The main goal of operational management of the implementation of programs for the development of WME should include ensuring the achievement of the goals of WME development, defined in the strategic planning and specified in the process of implementing the strategic plan through the formation of defense procurement plans.

Crisis phenomena are usually the cause of a problem situation in the process of operational management, i.e. a

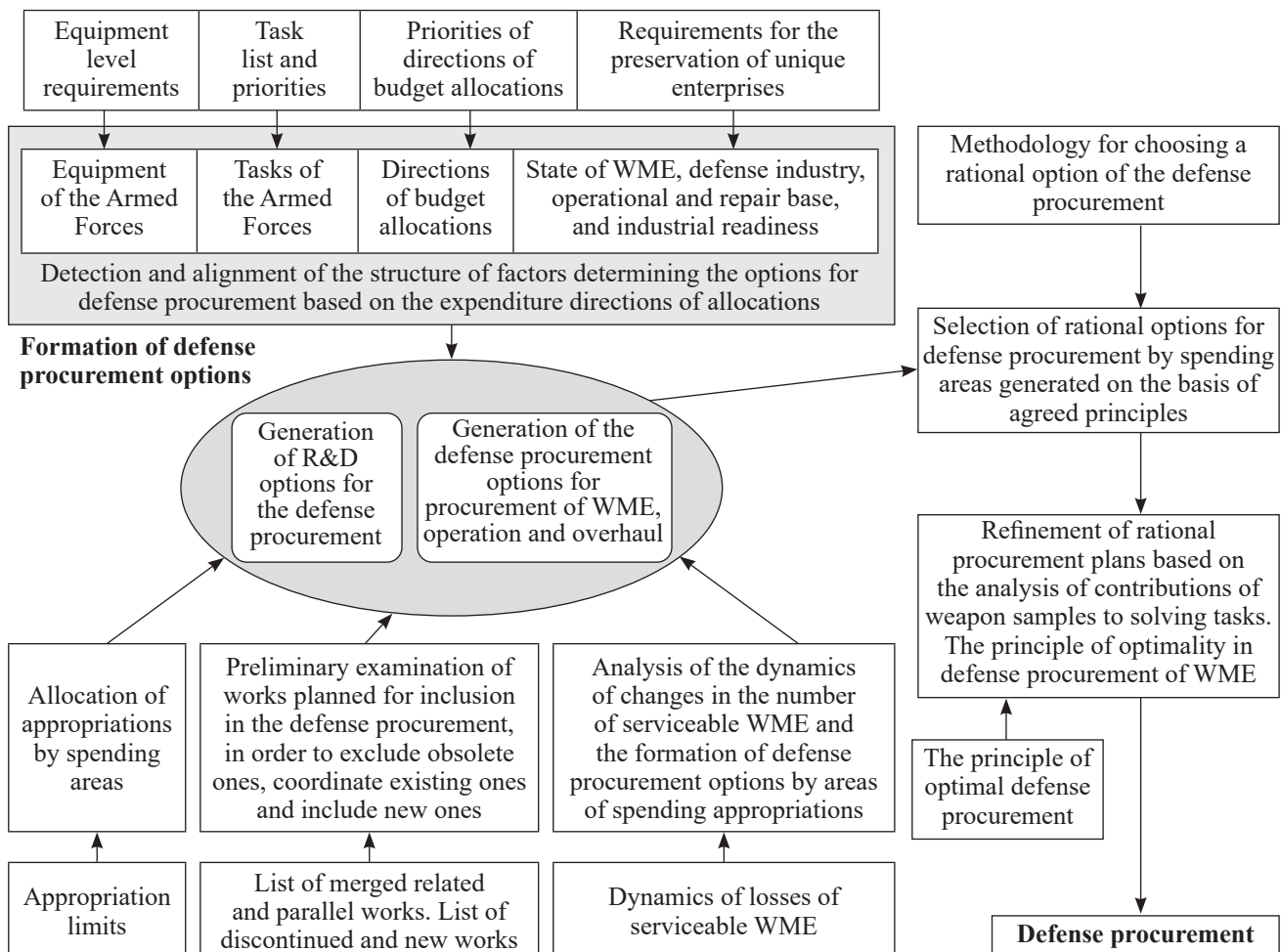


Fig. 3. Formation of a rational option for defense procurement of weapons and military equipment

situation in the state of the object of management in which there is a discrepancy between the required and realized values of target indicators. Tasks that have to be performed to resolve a problem situation are situational tasks.

The introduction of elements of situational management can allow to move from the technology of program management of WME development to the combined technology of program and situational management, which most adequately meets modern conditions, since it provides a prompt response of the management system and its timely adaptation to changing conditions in the implementation of programs for the development of WME [5].

A problem situation that has arisen or is predicted in the process of implementing programs for the development of WME can be considered resolved only if the formulation and implementation of management decisions that eliminate the state of the object of management associated with the problem situation is carried out.

Situational analysis, which is carried out in the process of managing the development of weapons and military equipment, can be presented in the form of performing the necessary set of actions to scenario model the development of the situation, assessing the possibility and potential danger of a problem situation due to the implementation of risk factors and the level of expected damage, determining the available and required resource reserves and making management decisions on their basis to resolve the problem situation to prevent possible damage or minimize the level of damage already caused.

A scenario, as a means of describing the development of a situation, should reflect the processes of events and the relationship between them depending on time.

The most adequate apparatus for realization of forecasting the development of the situation can be attributed to the appropriate modeling on a computer. To this end, it is necessary to develop a mathematical model of the process, which should be based on the structure of a real functioning system of management of the development of weapons and military equipment. After linking the model to a real process, it can be used for the purposes of forecasting and simulating management, making decisions on solving a problem situation in the process of managing the development of WME.

This model should include such separate models as the model of the management object and models of all objects that define the problem situation. It should be aimed at solving research situational tasks and be adequate to them.

In general, it can be concluded that at present there is a significant difference in the achieved and required results in the field of WME development management. To eliminate it, it is necessary to conduct intensive research, both in practical and theoretical terms, taking into account the dynamic nature of operations (combat operations) [6].

Solving this scientific problem should be implemented taking into account the role and place of the situational approach in the overall technology of managing the development of WME. To do this, it is advisable to be guided, based on the peculiarities of the current conditions for the implementation of programs for the development of WME, by the following basic principles of the situational approach in operational management:

- scenario approach – development of a scenario for forecasting the development of the situation, determining the patterns and trends of its development;
- dynamism of the control cycle – correction of the control program in accordance with the forecast of a problem situation;
- redundancy – compensation of impacts based on the prompt formation of a reserve of resources at the expense of internal resources of the life cycle of a sample of weapons and military equipment;
- preventive – the use of pre-prepared options for solving a problem situation;
- efficiency – solving a problem situation before or in the process of its occurrence and development on the basis of automation of solving situational tasks.

When determining the role and place of the situational approach in the overall management technology, the process of managing the development of WME can be presented as a set of interdependent coordinated actions (events and works) aimed at achieving a well-defined goal: timely equipping the armed forces with the necessary WME models and ensuring the improvement of their tactical and technical characteristics, provided that the funds allocated by the state for defense needs are spent efficiently.

Conducting a situational analysis should include a set of steps shown in Fig. 4.

This sequence of stages of situational analysis and their main content allows us to build an appropriate information and logical scheme for conducting situational analysis in the process of implementing programs for the development of WME (Fig. 5).

This scheme is structured in 4 blocks:

- formation of scenarios and forecasting the development of the situation;
- assessment and recognition of the problem situation;
- selection of a strategy for solving a problem situation;
- formulation of a management scenario to resolve the problem situation.

For the qualitative solution of situational tasks, the methodological support should include the following methods: determination of situational factors characterizing the dynamics of the situation and risk factors; assessment of the degree of risk of a problem situation and the amount of possible damage; formation of specific solutions to prevent or resolve a problem situation based on the synthesis of the relevant management scenario.

The methods for solving problem situations in the process of implementing programs for the development of WME should also include methods for determining the required amount of resource reserve to compensate for uncertainty factors, assessing the internal resource reserves of the plan, determining the required amount of additional funds to eliminate temporary and quantitative and qualitative deviations and rational redistribution of funds between the plan's activities based on the internal resource reserve.

Resources include the supporting components of the activity, including performers, energy, power, materials, equipment, etc.

The reserve of resources is the stock of resources, which is defined as the difference between the required and

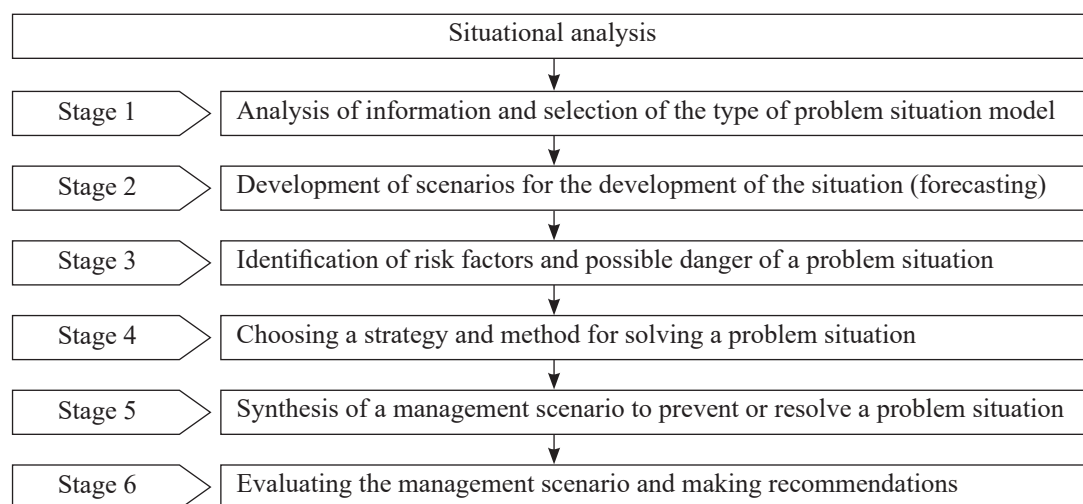


Fig. 4. Stages of situational analysis and their content

actual volume of activity components in the process of managing the development of WME. Taking into account the hierarchical structure of the WME development management system, the following hierarchy of resource reserves can be proposed by management levels:

- level of state administration – reserve of the current state budget;
- the level of the Ministry of Defense – a reserve by the level of solving strategic tasks, by the items of financing the development of the armed forces and their weapons system in the planning period, etc.;
- the level of general customers – reserve by tasks (operational, tactical, tactical), by programs (program sections in the part related to this customer), by types of WME, by complex-targeted programs, by cooperation.

Resource reserves can be defined as key factors for ensuring the sustainability of WME development management (plan sustainability).

Management of resource reserves consists in the implementation of a set of measures to determine the required volume, timely replenishment and use at the right time of the implementation of programs for the development of WME. The analysis of significantly changed conditions and the difficult predictability of their dynamics indicate the need to put forward new, more stringent requirements for the system of automated management of the development of weapons and military equipment. To implement them, appropriate software and tools for situational analysis and modeling are needed (Fig. 6).

The main task that arises during the development of software tools is the need to unite and combine in a single system such disparate elements as non-formalized human activity, mathematical models and formalized algorithms.

As requirements for the organization of modeling for decision-making on solving problem situations, the following can be considered:

- organization of iterative procedures with the possibility of step-by-step adjustment of initial data and decisions;
- use of information in convenient formats and volumes at each iteration;
- the possibility of making a clear, meaningful interpretation of each cycle of iterations and its result;

- the possibility of choosing a different degree of automation of operations in each iteration;
- convergence of the iterative procedure to the best solution for an acceptable number of iterations;
- natural calculation rhythm (response time, including input and output of data) when solving tasks;
- obtaining a decision in the required time, taking into account the real organization of the structure, the real capabilities of technical means for obtaining and processing information.

The general requirements that determine the viability of software and instrumental means of situational analysis are to ensure the ability to:

- obtaining rational solutions to prevent or resolve problematic situations while reducing labor and time costs;
- development, operational modernization and adaptation in the process of operation (expansion of the list of tasks, data, improvement and replacement of algorithms for calculating the values of indicators of the state of typical objects with more perfect ones, etc.).

In order to meet the listed requirements, software tools for situational analysis and modeling should serve as the basis of automated technology that implements a regulated iterative process of processing input information into output management decisions to solve a problem situation. When building this technology, it is advisable to use a package approach – forming a set of modules that cover the subject area of situational analysis and modeling in the process of managing the implementation of programs for the development of WME. The step-by-step iterative nature of the task-solving procedure for solving the problem situation is determined by the need for consistent adjustment of goals, means and methods of influence in solving the problem situation.

When choosing solutions, it is necessary to focus on their validity, compliance of the solution with the set goal, completeness of consideration of limitations. When developing software tools, it is necessary to be guided by such principles as purposefulness, reasonableness, iterability, content of information, control, etc. The basic stage of development of software tools should be the stage

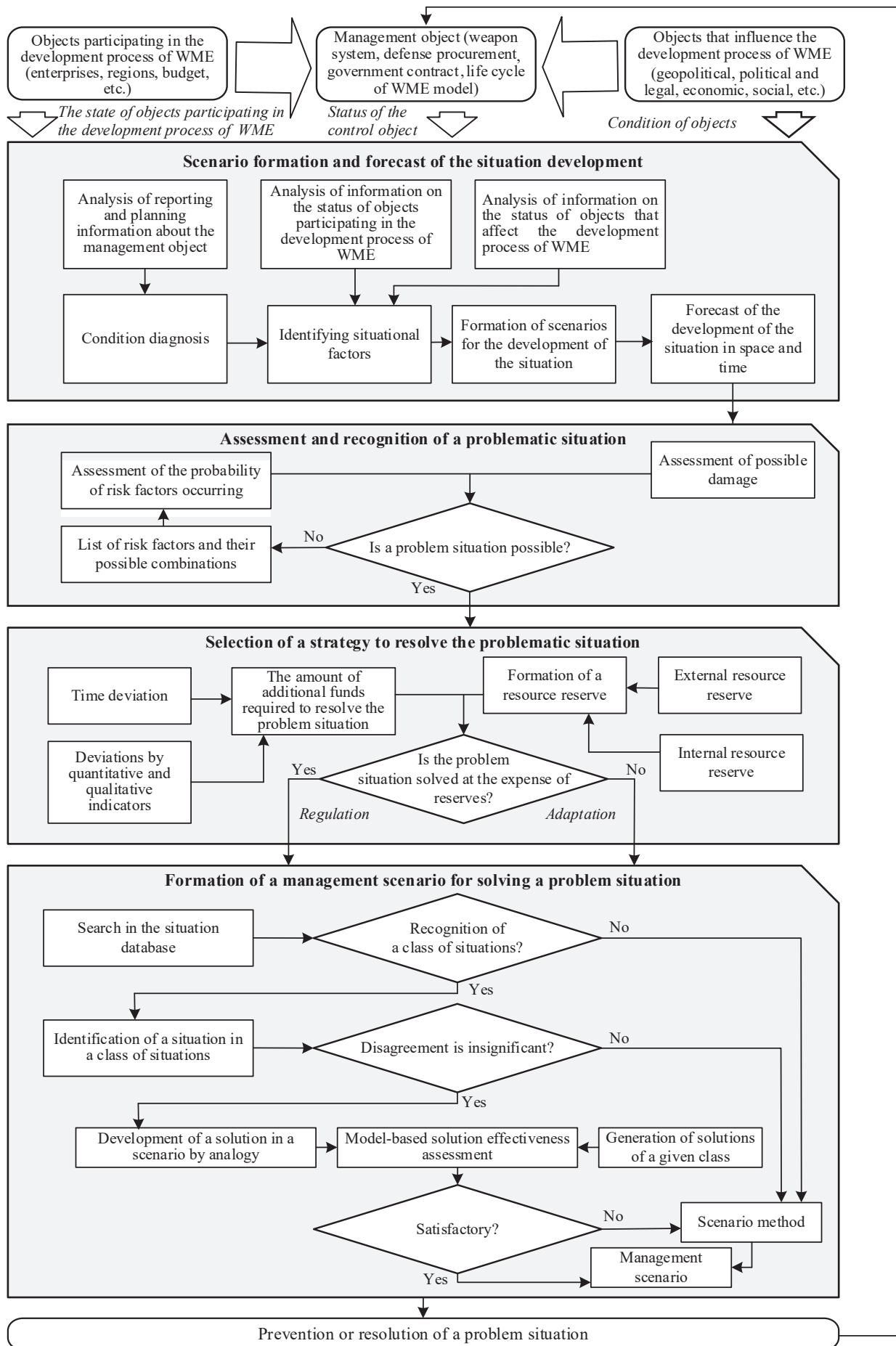


Fig. 5. Information and logic diagram of the situational analysis

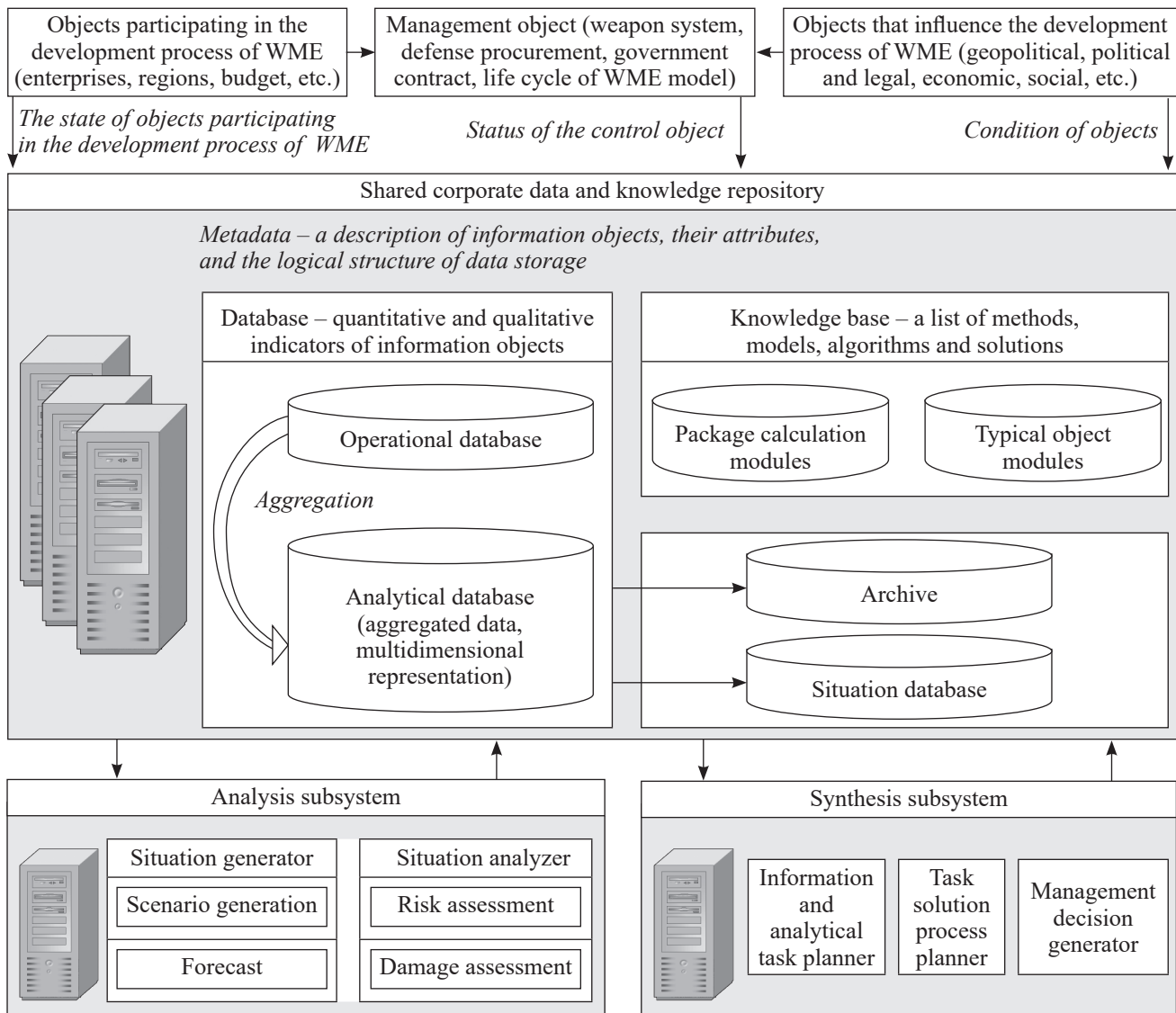


Fig. 6. Structural diagram of software and tools for situational analysis and modeling

of building models of typical objects that participate in the process of development of WME and influence this process and their implementation based on the use of software tools of situational analysis.

CONCLUSIONS

Management of the process of development of weapons and military equipment should be carried out by a management system consisting of a hierarchical structure of management bodies; systems of typical documents of different forecast depth; measures for substantiation, formation, control of implementation and adjustment of planning decisions; methods of scientific substantiation of management functions on the basis of their formation; information and legal space, mathematical and software tools, a program-situational approach to the implementation of programs for the development of weapons and military equipment within the framework of a single process of comprehensive technical equipment of the armed forces based on capabilities, taking into account the manifestation of uncertainty and risk factors, the dynamics of their change.

The methodical provision of situational analysis in the process of managing the development of WME should

include methods that allow: to determine the factors that characterize the dynamics of the development of the situation (situational factors); assess the risk of a problematic situation when they change; recognize problematic, unfavorable and critical situations; to produce specific decisions regarding their solution.

Also, the scientific and methodological apparatus for solving problem situations in the process of implementing programs for the development of WME should include methods for determining the required amount of resource reserves to compensate for uncertainty and risk factors, evaluating the internal reserves of plan resources, determining the required amount of additional means to eliminate deviations that have arisen, rational redistribution of funds between the works of the plan based on the internal reserve of resources.

Software-instrumental means of situational analysis should form the basis of automated technology that implements a regulated process of processing input information into output management decisions for solving problem situations. When implementing this technology, it is necessary to include: a system-wide data and knowledge

repository as part of an operational and analytical information database, a situation database and a knowledge database. As a basic component of software tools, models of typical objects that participate in the development of WME and influence this process should be defined.

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КОНЦЕПТУАЛЬНО-МЕТОДИЧНІ АСПЕКТИ УПРАВЛІННЯ ПРОЦЕСОМ РОЗВИТКУ СИСТЕМИ ОЗБРОЄННЯ ЗБРОЙНИХ СИЛ ДЕРЖАВИ ПРИ ДИНАМІЧНІЙ ЗМІНІ ЗОВНІШНІХ І ВНУТРІШНІХ ФАКТОРІВ В УМОВАХ НЕВИЗНАЧЕНОСТІ ОБСТАНОВКИ ТА ПРОЯВУ ФАКТОРІВ РИЗИКУ

У статті на концептуально-методичному рівні розглядаються основні положення управління розвитком системи озброєння збройних сил держави в сучасних умовах. Пропонується використовувати технологію управління, що поєднує методи програмно-цільового планування розвитку озброєння та військової техніки та методи ситуаційного аналізу у процесі реалізації програм цього розвитку в умовах наявності факторів невизначеності та прояву ознак ризику.

Стверджується, що має місце протиріччя в практиці між глибиною достовірного прогнозу макроекономічних програм розвитку ОВТ та умов їх реалізації, які директивно задаються часовим інтервалом планування відповідно до вимог законодавства, яке регламентує процес класичного планування та управління розвитком ОВТ.

Виділено основні етапи проведення ситуаційного аналізу та розкрито їх зміст. Наведено склад програмно-інструментальних засобів ситуаційного аналізу та моделювання, орієнтованих на вирішення проблемних ситуацій, які виникають у процесі реалізації програм розвитку озброєння та військової техніки (ОВТ). Відображено положення про те, що ці програмно-інструментальні засоби мають складати основу автоматизованої технології переробки інформації, що надходить, в управлінські рішення щодо вирішення проблемних ситуацій.

Важливе значення надається формуванню резерву ресурсів для запобігання чи вирішенню проблемних ситуацій. Розглянуто інформаційно-логічну схему проведення ситуаційного аналізу в процесі реалізації програм та планів розвитку ОВТ.

Ключові слова: *проблемна ситуація, фактори невизначеності та ризику, ситуаційний аналіз, ситуаційне завдання, резерв ресурсів, автоматизована технологія управління, система управління.*

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DOI: [https://doi.org/1034169/2414-0651.2025.1\(45\).29-38](https://doi.org/1034169/2414-0651.2025.1(45).29-38)**O. O. HOLOVIN**, *Doctor of Technical Sciences**Senior Research Fellow*<https://orcid.org/0000-0003-4662-4559>**V. L. PALIY**<https://orcid.org/0009-0008-0458-3289>*(Central Scientific Research Institute of Armament and Military Equipment of Armed Forces of Ukraine, Kyiv)*

ORGANIZATIONAL ASPECTS OF THE SYSTEM OF TECHNICAL INTELLIGENCE OF WEAPONRY AND MILITARY TECHNOLOGIES IN NATO COUNTRIES

The study and scientific-technical analysis of samples (fragments) of the enemy's military equipment (ME) is an integral part of maintaining the defense capability of the state and is critically important for effective defense and deterrence in modern conditions.

The article discusses the organization of scientific-technical and technical intelligence systems, as well as the technical operation of NATO countries. It shows the purpose of each of these processes, their components and the results to be achieved.

A typical list and content of reports formed as a result of the relevant studies are provided.

It is determined that, in modern conditions, the effective implementation of NATO approaches to scientific-technical analysis of samples (fragments) of the enemy's ME in Ukraine requires the development of an appropriate scientific-methodological framework for conducting research.

Keywords: *scientific-technical intelligence (S&TI), technical intelligence (TECHINT), technical operation (TO), weaponry and military equipment.*

Modern armed conflicts are characterized by the rapid development of technologies that constantly alter the balance of power on the battlefield.

The military aggression of the Russian Federation against Ukraine further demonstrates the high relevance of conducting scientific research on captured enemy weaponry (fragments left after their use). The results of these studies not only allow for the assessment of the enemy's technical capabilities but also help to identify their vulnerabilities, develop effective countermeasures and improve domestic military technologies.

The purpose of this article is to analyze approaches to conducting such research in NATO countries, determine their impact on military science and practice and justify the necessity of developing an appropriate scientific-methodological framework for the technical analysis of enemy weaponry and military equipment (ME) samples.

Modern weapon systems, such as UAVs, ballistic and cruise missiles and electronic warfare tools, which are actively used by the Russian Federation against Ukraine, highlight the exceptionally high pace of military technology development and the creation of new threats to Ukraine's defense forces in repelling armed aggression.

Consequently, the study and scientific-technical analysis of enemy ME samples (fragments) create opportunities for:

- identifying new technologies before they become widespread, enabling quick adaptation to changes on the battlefield while maintaining a technological advantage and more effectively countering new challenges;
- the evaluation of the combat effectiveness of enemy weaponry samples involves determining their actual technical characteristics (ATH), which may differ from those officially published;
- the development of effective methods for neutralizing enemy weaponry and countermeasures based on data regarding identified weaknesses in applied designs or technologies, as well as data on suboptimal technical decisions made by developers during the design of weaponry samples, is also crucial;
- moreover, the development and improvement of domestic weaponry can be achieved by integrating elements of enemy technologies into domestic systems;
- this process facilitates the operational decision-making of command on force deployment, strategy development and operation planning based on more accurate assessments of the enemy's intentions and strategies;
- furthermore, the identification of sources and supply channels of weaponry and its components to the enemy and the implementation of corresponding sanctions policies are also key outcomes of such studies;
- the evaluation of the technological potential of an enemy state and forecasting its further development, as well as identifying technological capabilities, such as the level of weaponry development, applied materials and components, as well as innovative solutions, are integral parts of these analyses;
- new tactical approaches in response to the capabilities of the enemy can also be formulated and collective security can be strengthened by pooling resources for conducting expertise and exchanging information between NATO countries and partner states, which ensures collective readiness to respond to new threats;
- the fight against the proliferation of dangerous technologies is another outcome, based on information about discovered technologies and materials that may pose a threat (such as chemical, biological, or nuclear weapons).

Thus, the study of weaponry samples (fragments) of the enemy is an essential part of maintaining the defense capability of the state and their relevance lies in ensuring technological, informational and strategic advantages, which are critically important for effective defense and deterrence in modern conditions.

In NATO, scientific research on captured enemy weaponry samples (fragments left after their use) is conducted within the framework of the existing intelligence system.

This is due to the fact that intelligence operations provide a comprehensive assessment of current and future threats,

a systematic approach to analyzing samples by integrating data from various sources and ensure a thorough analysis and maximum effectiveness of using the obtained data to achieve NATO's strategic and tactical objectives.

According to the provisions of the Joint Intelligence, Counterintelligence and Security Doctrine [1], the components of this system (Fig. 1), within which the study of enemy weaponry samples (fragments) is carried out, include Scientific and Technical Intelligence (S&TI) and Technical Intelligence (TECHINT).

One component of TECHINT is Technical Exploitation (TE).

S&TI (strategic level of research) examines foreign developments in the field of fundamental and applied sciences, materials and technologies that may potentially be used for military purposes, specifically to improve weapon systems. S&TI is a critical component of national security, as the dynamic nature of modern warfare and the continuous evolution of threats require weapon systems to be adaptable to these threats and scalable [2, 3].

Within the S&TI process, based on the assessment, analysis and interpretation of foreign scientific-technical information, the characteristics of weapon systems, their capabilities, vulnerabilities, limitations, effectiveness and the industrial potential of countries are studied. R&D results, within which certain weapon systems and technologies for their production are developed, are also examined.

This area of intelligence also involves evaluating the scientific and technical achievements of the enemy and their potential for the development or improvement of domestic strategic technologies.

In addition, within the framework of S&TI, the creation of prototypes and their testing is carried out to accelerate the implementation of new technologies or capabilities into prospective weapon systems (WS). Examples of S&TI products include the characteristics of weapon systems, their capabilities, vulnerabilities, effectiveness and limitations regarding their use [4].

Thus, the results of S&TI are used to provide early warnings about foreign technological developments and capabilities, as well as to consider them when conducting domestic R&D for the development of weapon systems. TECHINT is a broad field of intelligence activity, encompassing the collection, analysis, forecasting, use and dissemination of information on technical devices, systems and equipment.

The Joint Publication 1-02 [5] defines TECHINT as intelligence data obtained through the collection, processing, analysis and use of information concerning foreign equipment and material means to prevent technological surprise, assess foreign scientific-technical capabilities and develop countermeasures to neutralize the enemy's technological advantages.

Another definition of TECHINT is given in AAP-06 (NATO GLOSSARY OF TERMS AND DEFINITIONS (ENGLISH AND FRENCH)), which states: «Technical Intelligence – intelligence information regarding foreign technological developments, the effectiveness and operational capabilities of foreign material means, which have or may have practical military applications» [6].

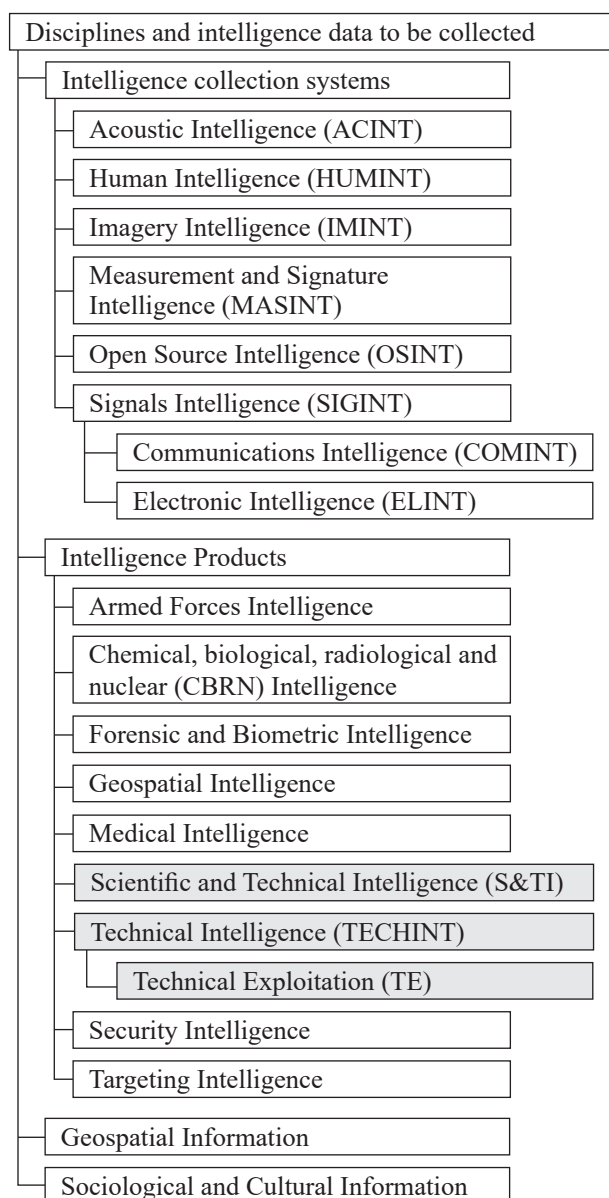


Fig. 1. Main components of the intelligence system of NATO countries

The Joint Publication on Joint Intelligence JP 2-0 [7] defines TECHINT as intelligence data obtained through the use of foreign materials for strategic, operational and tactical level command. Accordingly, the aim of TECHINT is to assess the enemy's potential and vulnerabilities in their technology, as well as to provide baseline data for long-term planning and forecasting.

The mission of TECHINT involves [8]:

- preventing the unpredictable development of enemy technologies and maintaining a technological advantage over them;
- providing intelligence data to the command to improve awareness of the enemy and develop protective measures for own forces;
- developing and applying effective measures to target the enemy's weapon systems;
- ensuring individual, timely and precise TECHINT support for personnel throughout the entire spectrum of military operations;

- conducting technical intelligence and assessing the technical capabilities of the enemy.

During combat operations, the TECHINT mission also involves the exploitation of captured or transferred enemy weaponry and accompanying documentation. TECHINT is a valuable tool for supporting the actions of unit commanders, as it enables early identification of the enemy's technical capabilities, vulnerabilities and intentions and facilitates the rapid development of countermeasures.

Since the enemy may temporarily achieve technological parity or superiority by acquiring modern weapon systems or acquiring certain capabilities, a coordinated TECHINT program is crucial to ensure the rapid and effective neutralization of this parity or advantage within the scientific-research process.

TECHINT includes the evacuation, identification, collection, evaluation and use of captured enemy equipment in accordance with technical intelligence requirements.

The process of executing TECHINT operations in a multidomain environment begins at the service level. Ground forces and the Air Force have specialized TECHINT units to support weapon system capture operations and analysis. Additionally, each service has TECHINT personnel who provide support and expertise on matters related to activities in this field.

Unified teams play an important role in implementing TECHINT tasks. Each joint command must have an officer within the intelligence staff (J-2) responsible for planning TECHINT and coordinating activities with national intelligence analysis centers and the joint staff.

NATO has a clearly structured approach to studying captured enemy weaponry samples. This process encompasses several key stages that help gather valuable information on enemy military technologies. Fig. 2 presents the TECHINT process algorithm.

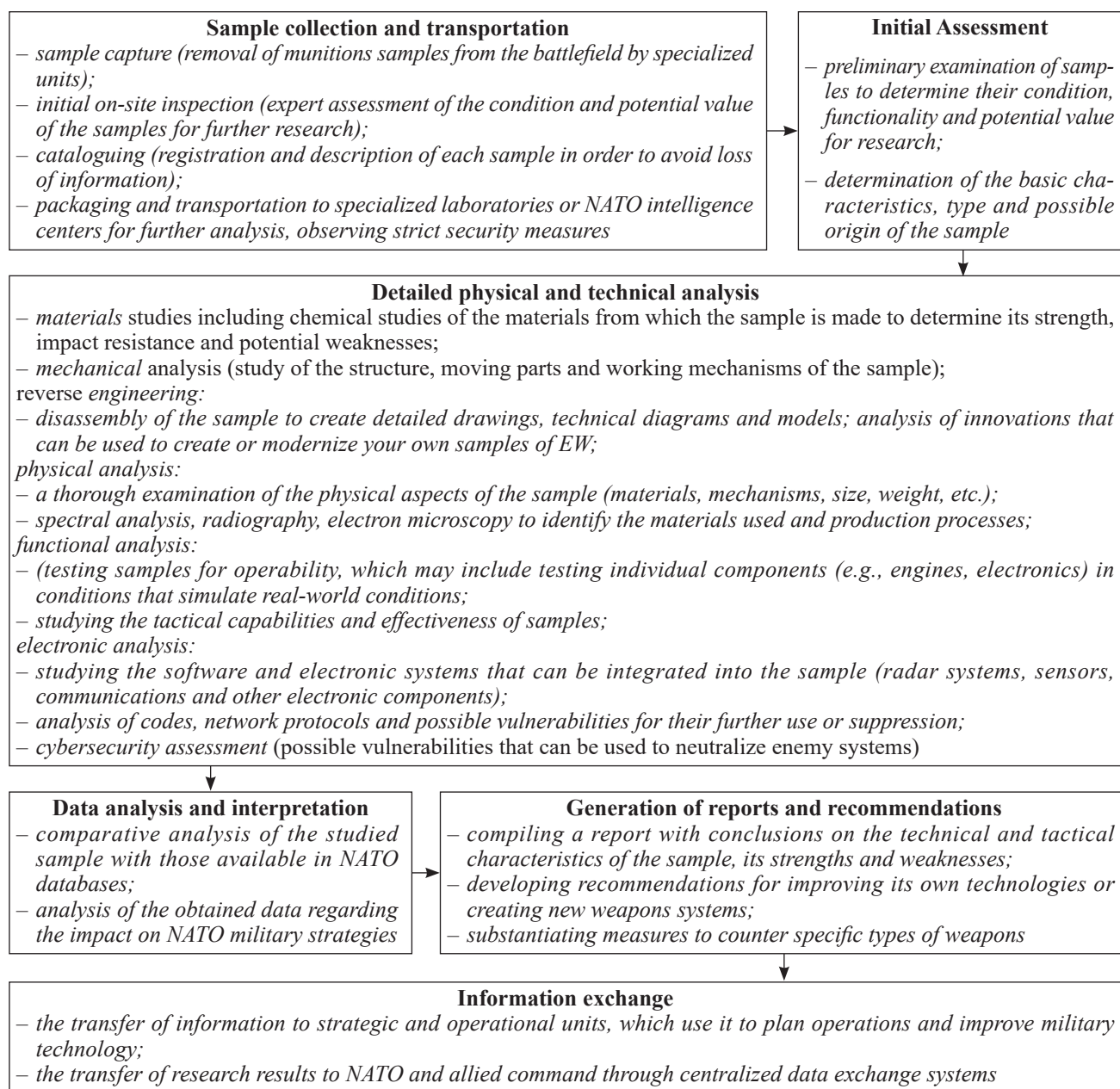


Fig. 2. TECHINT algorithm

A variety of approaches are used in the TECHINT process, each of which is aimed at the most effective collection, analysis and use of technical information. The main ones are shown in Fig. 3.

The movement of captured weapons samples between institutions and military command bodies in NATO countries is carried out according to a strictly regulated procedure. This process includes several stages and ensures the most effective use of the obtained data for operational, technical and strategic purposes.

Thus, at the first stage, after the capture of a weapon sample by military units or specialized teams, its identification (determination of the type and condition of the sample, assessment of its value), documentation (photography, description of technical characteristics and registration) and marking for transportation are carried out.

Next, the samples are transported to operational analysis centers (national intelligence centers) for initial technical analysis (checking for hidden explosive devices and means of self-destruction, obtaining initial data on the functioning of the system, analysis of software and data that may be stored in the system).

At the next stage, the samples are transferred to specialized laboratories or research institutions for detailed scientific and technical analysis. The direct process of moving TECHINT data from the teams that captured EW samples to national intelligence centers is shown in Fig. 4.

The result of TECHINT can be strategic reports, analytical assessments, forecasts or recommendations.

Reports on the results of the analysis are provided to national intelligence centers. If the sample is of strategic importance, then for coordination with other NATO member states, the results of the analysis are transmitted to the general structures of the Alliance, in particular the NATO Intelligence Fusion Centre (NIFC), the NATO Communications and Information Agency (NCIA) and the Science and Technology Organization (STO).

During combat operations, the operation of captured or transferred enemy weapons and accompanying documentation is added to the TECHINT mission. Priority in the evacuation of captured munitions is given to radio-electronic systems and means of communication, ammunition and explosives, technical documentation (firing tables, logbooks,

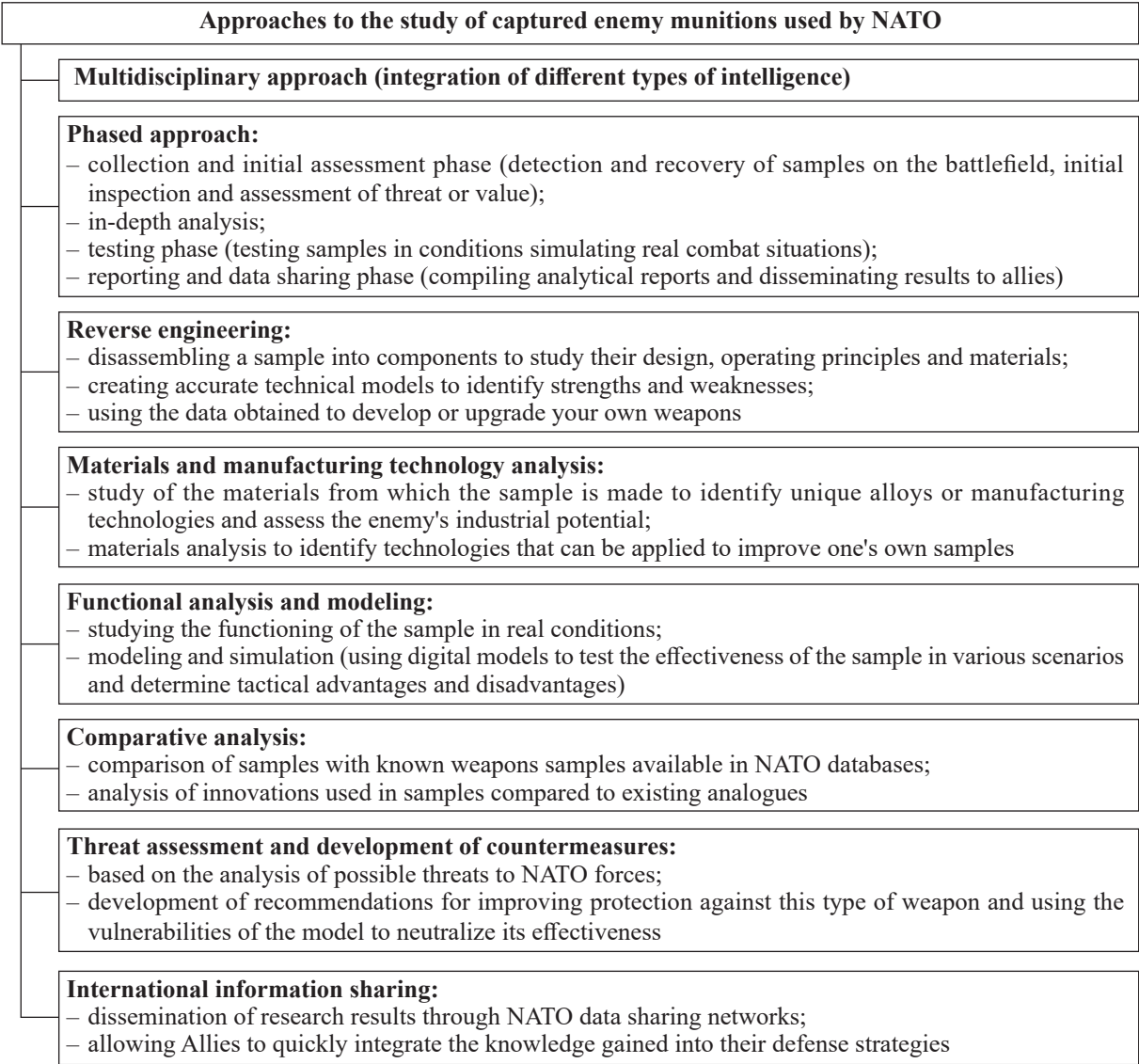


Fig. 3. Approaches to the study of captured enemy munitions samples

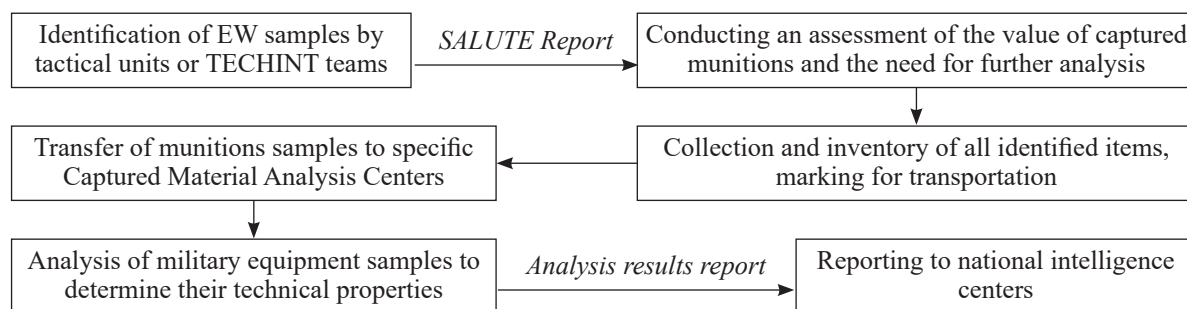


Fig. 4. The process of moving TECHINT data from teams that captured EW samples to national intelligence centers

technical descriptions and operating instructions for munitions).

Data obtained through TECHINT is an important component of Joint Intelligence, Surveillance, and Reconnaissance (JISR). Within NATO, this concept involves the integration of different sources and types of intelligence to obtain a complete understanding of the battlefield situation and support decision-making at the operational and strategic levels.

TECHINT complements other types of intelligence, such as SIGINT (signals intelligence), IMINT (imaging intelligence), HUMINT (human intelligence) and provides deeper technical analysis, which increases the overall effectiveness of JISR and the speed of response to threats.

Data obtained through TECHINT also contribute to the formation of tactical and strategic lessons that are taken into account during exercises and operations, which is an integral part of the Lessons Learned processes. TECHINT results allow for the improvement of tactical techniques and the introduction of innovations in weapons models, which provides NATO with the ability to adapt to rapidly changing technological challenges [9, 10].

TECHINT is also linked to NATO's defense planning processes (NATO Defense Planning Process, NDPP), in particular:

TECHINT provides critical information for identifying technological threats that may arise from potential adversaries, which is taken into account in the NDPP when developing requirements for new weapons systems or modernizing existing ones;

data obtained through TECHINT is used in developing capability requirements, namely when determining the technological needs of the NATO defense system to effectively counter new threats.

Thus, TECHINT is integrated into numerous NATO processes, which allows the alliance to quickly adapt to new technological challenges. According to the above algorithm, various institutions and bodies are involved in S&TI, TECHINT and TE in NATO countries, in particular:

in the USA:

Defense Intelligence Agency (DIA) – conducting S&TI and TECHINT on the latest weapons and technologies of the enemy;

National Security Agency (NSA) – TECHINT related to electronic communications;

Central Intelligence Agency (CIA) – S&TI on assessing the scientific and technical capabilities of other states;

National Ground Intelligence Center (NGIC) – research on ground weapons (armored vehicles, air defense systems, artillery);

Naval Surface Warfare Center (NSWC) – research on naval weapons, captured ships, submarines and their systems;

Air Force National Air and Space Intelligence Center (NASIC) – research on aviation equipment, captured aircraft, drones and air defense systems;

in the UK:

Defense Intelligence (DI) – organization of military intelligence, including S&TI and TECHINT;

Government Communications Headquarters (GCHQ) – provision of technical intelligence in the field of cybersecurity and electronic intelligence;

Defense Science and Technology Laboratory (DSTL) – research on the technological complexity of captured weapons samples;

Intelligence, Surveillance and Reconnaissance (ISR) – implementation of TECHINT of captured equipment and its electronic systems;

Defense Equipment & Support (DE&S) – coordination of technical analysis of captured weapons;

In Germany:

Bundesnachrichtendienst (BND) – performance of S&TI tasks, in particular in the field of industrial and technological intelligence;

Amt für den Militärischen Abschirmdienst (MAD) – TECHINT;

Bundeswehr Technical Center (Wehrtechnische Dienststellen, WTD) – TECHINT;

Bundeswehr Geoinformation Center – study of navigation and communication systems of captured equipment;

In France:

Direction Générale de la Sécurité Extérieure (DGSE) – conduct of external intelligence, including S&TI;

Direction du Renseignement Militaire (DRM) – performing military intelligence tasks, including TECHINT;

Direction Générale de l'Armement (DGA) – conducting TE of captured weapons, their technological and combat capabilities;

Centre de Recherche et d'Études en Aérospatiale et Défense (CREAD) – research into aerospace systems and air defense;

in Canada:

Canadian Security Intelligence Service (CSIS) – conducting scientific and technical intelligence in the context of threats to national security;

Communications Security Establishment (CSE) – TECHINT in the field of information security;

Defense Research and Development Canada (DRDC) – research into captured equipment for the adaptation of new technologies;

Canadian Forces Intelligence Command (CFINTCOM) – S&TI of captured weapons systems.

A narrower and more practical TECHINT process focused on obtaining and using materials and technologies for further exploitation is Technical Exploitation [11, 12].

The term TE is used as a universal one, reflecting the full complexity of the approach and covering [12]:

- analysis and assessment of the technical characteristics of EW samples;

- development of countermeasures;

- integration of results into future military operations;

- potential use of captured samples in one's own interests.

The process of technical analysis involves the application of scientific methods to gain additional knowledge and understanding of information about material assets, which allows commanders and staffs to obtain reliable data about the operational environment. Material assets can include documents, electronic components and media, weapons, explosives and other relevant materials [12].

The main principles of technical analysis are as follows [11]:

- clear, consolidated process management and control through the Joint Intelligence Staff (CJ2), coordination of technical operations activities with other personnel elements and units;

- preservation of personnel lives (awareness of risks and weighing them against the value of information that can be obtained from operations activities);

- preservation of material assets (using optimal documentation methods and procedures that are least invasive and destructive);

- high-speed technical operation processes that allow for rapid dissemination of critical information and materials;

- introduction of a methodology and system for sorting and prioritizing material assets based on their importance and the safety of personnel;

- management of the organization's information resources by processing knowledge obtained by one or many different individuals and institutions for the purpose of exchanging information with NATO and other partners, archiving data.

Technical analysis is carried out at three levels [11, 12]:

- field/tactical level, considered in [12];

- theater level (operational);

- strategic level (outside theater level).

TE tasks within the framework of defined capabilities at the strategic level are reflected in [11].

Thus, the S&TI, TECHINT and TE processes are determined by different tasks of military technical intelligence, in particular:

S&TI focuses on the analysis of scientific and technical aspects of potential threats, which includes the study of technologies, scientific research, engineering developments and technical capabilities of the enemy and covers the processing of a wide range of scientific and technical

information and the analysis of scientific and technical innovations that are important for national security;

TECHINT includes various aspects of technical intelligence, from the study of technological systems to innovations, with a special emphasis on military and strategic applications in order to assess the potential and vulnerability of enemy technologies, as well as develop countermeasures strategies;

TE focuses on the in-depth analysis of specific physical objects or materials in order to obtain detailed technical information about them for operational and strategic use [12]. An important task that is solved in the course of S&TI, TECHINT and TE is the formation of relevant reports based on the results of research. At the moment, there is no standard document in NATO that would regulate the structure of reports developed based on the results of research [12].

However, a typical list of technical intelligence reports and their content can be presented as follows [8]:

1. SALUTE (size, activity, location, unit/uniform, time and equipment) report.

This report is compiled by tactical units or TECHINT teams and is used to quickly report on the capture of enemy materials.

The SALUTE report contains data on:

- the number and type of captured enemy EW samples;

- the circumstances of the capture;

- the location (coordinates) of the capture;

- the presence of camouflage, tactical signs, markings, inventory number and series on the sample;

- the unit that captured the EW sample;

- the date and time the EW sample was discovered;

- additional equipment and ammunition that was captured together with the EW sample.

2. Preliminary technical report (PRETECHREP) – a preliminary technical report.

PRETECHREP contains the following data:

- the type of captured equipment and its quantity;

- date and time of capture;

- location (coordinates) of capture;

- unit that carried out the capture and circumstances of capture;

- enemy formation from which it was captured;

- brief description of the captured munitions with serial numbers;

- important technical characteristics and photographs;

- time of sending the Report;

- current location of the captured munitions.

Also, when forming PRETECHREP, the report must include data on all radio frequencies of communication equipment, serial markings of equipment and combat damage caused by the captured munitions.

3. Complementary technical intelligence report (COMTECHREP) – Additional technical intelligence report.

COMTECHREP contains a more detailed description of the captured munitions than PRETECHREP and informs Research Centers and tactical units about the significant detailed technical information received.

Thus, the Report contains data on:

the design of the sample (dimensions, materials, production technology), key components, schemes or drawings;

unique or innovative technical solutions;

comparison with similar systems of our own production or samples of allies;

evaluations of functional characteristics obtained from test results;

evaluations of the effectiveness of the sample in combat conditions;

identified vulnerabilities and shortcomings;

the potential for using the enemy's technologies in our own defense sector;

proposals for creating our own technologies based on captured ones, or improving existing ones;

analysis of the enemy's technological base;

possibilities for creating countermeasures or using technologies to modernize our own systems.

4. Multi-service complementary technical intelligence report (MULTI-SERVICE COMTECHREP) – multi-service additional technical intelligence report.

This report is submitted as soon as possible and is used to report on all items that are not related to explosive ordnance.

The following is an example of a multi-service COMTECHREP:

date and location of the sample (map coordinates);

type of equipment captured and its quantity;

origin of the sample;

description of the sample with external features;

condition of the equipment;

technical characteristics of immediate tactical significance (additional details);

recommendations for disposal;

nameplates with photographs;

other information;

tasks of the TECHINT collection group performing this initial analysis;

time of sending the report.

5. Complementary technical intelligence report – type B (COMTECHREP – TYPE B) – Complementary technical intelligence report – type B.

COMTECHREP – type B is used to report on detected explosive ordnance. This report should be as complete and detailed as possible.

The table of contents should include the following elements:

date and location of capture;

country of manufacture, designations and identification marks;

description;

overall length including fuse and dimensions of tail, blades, control surfaces and fittings measured in various states;

maximum diameter of each element;

description of shape, design and internal configuration (streamlines);

span of blades and control surfaces;

number, relative position and dimensions (width, length) of control surfaces;

thickness of hull (nose, skids, main body);

type and materials of hull and control surfaces;

color and marking (nose, main body, tail and blades);

weight (with fuel and empty);

nature of filling, e.g. submunitions or solid charge;

method of application, e.g. spray or airburst;

description of warhead (if any), material and its geometric dimensions;

type of missile guidance system and methods of its stabilization in flight;

values of frequencies used for targeting;

description of non-contact detonator (if any);

electronic countermeasure system and equipment for scattering dipole reflectors (if any);

description of seeker and its design;

diameter of fairing and dimensions of seeker antenna (if any);

dimensions (internal and external) of waveguides in the homing head, as well as waveguides and/or antennas in the wings or hull, description of the technology used;

shape and dimensions of the torpedo, method of movement and propeller data;

system detonation, fuze system (nose, tail or cross) and details of the triggering mechanism;

type of suspension, with details of devices used, such as electrically operated shrouds or release mechanisms;

other information (including an estimate of the time required to prepare the object for shipment to a technical intelligence center or designated industrial facility for detailed analysis);

name of the officer in charge of the technical team conducting the investigation;

time of notification;

time required to complete the investigation;

preliminary set of photographs to be sent with the report.

6. Nine line unexploded ordnance/improvised explosive device spot report – Nine line report on the detection of explosive objects (unexploded ordnance / improvised explosive devices).

In the event of the detection of mines, explosives or other explosive objects, a report must be made to the tactical operations center in the following format:

date and time of detection of the object;

reporting organization (unit identification code) and location of the detected object;

means of communication (radio frequency, call sign, contact person and telephone number);

type of munition (dropped, launched, installed or thrown), dimensions of the danger area (if known), number of objects, details of size, shape, color and condition (intact or damaged);

presence of chemical, biological, radiological or nuclear contamination;

equipment, facilities or other assets that are at risk in the event of an explosive object being detonated;

description of the current tactical situation (the impact of the presence of an explosive object on the task);

description of the measures taken to protect personnel and equipment;

recommended priority for the response of demining technicians or engineers.

7. Detailed technical report (DETECHREP) – detailed technical report.

Information about the structure of the report is not available in open publications, since it is usually classified. However, in the USA, such a report is prepared at the Center for Military Equipment Operations (CMEC) with the assistance of scientific and technical information (S&TI) analysis personnel and is sent to the units responsible for organizing the examination (S&TI) and its abbreviated version – to the units directly conducting combat operations.

8. Technical intelligence summary – a summary report of technical intelligence.

This report is formed on the basis of the results of the analysis of several captured samples of munitions that affect tactical operations within a certain theater of operations. Information for the report comes from preliminary technical reports (PRETECHREPs) and technical communication reports (COMTECHREPs), which are collected over a period of time or from a large technical information collection facility.

9. Technical intelligence report (TIR) – Technical intelligence report.

A TIR is a critically important report that is sent to the highest levels of the intelligence hierarchy and is always classified. The report is based on information from preliminary technical reports (PRETECHREPs), additional reports (COMTECHREPs) and detailed technical reports (DETECHREPs).

Thus, it can be stated that the results of S&TI, TECHINT and TE are of critical importance for ensuring national security, technological leadership and competitiveness of the state, as well as for adapting to rapidly changing challenges.

The main areas of use of these results include:

- assessment of threats and potential of the enemy (analysis of military technologies, weapons, tactics and strategies of the enemy);

- integration of identified modern technologies into promising weapons;

- creation of technologies for protection against enemy weapons;

- determination of priorities for the development of new weapons systems and technologies;

- assessment of technical achievements of other countries to predict the development of critical technologies in the world and the formation of key directions of technological development of the state.

Given the content of the reports, it can be concluded that their formation requires the use of an interdisciplinary approach, in particular, the involvement of specialists from various fields: engineers, analysts, cryptographers, electronics specialists and others. Also, the reports should integrate data from various sources: intelligence, technical tests, open sources (OSINT), etc.

Currently, research is being conducted to improve the structure of S&TI, TECHINT and TE reports, in particular, in [12] the structure of a TE report at the strategic level is proposed.

It should be noted that Ukraine has not yet created an effective system of intelligence agencies and research institutions, like the leading NATO countries, which

complicates the conduct of S&TI, TECHINT and TE in the conditions of armed aggression of the Russian Federation against Ukraine.

At the same time, the key factor influencing the effectiveness of S&TI, TECHINT and TE tasks is the coordination of actions of personnel, teams and units.

Thus, during the Martial Vision exercises, it was established that the absence of a coordination group with TE (Technical Exploitation Coordination Cell) creates an «information vacuum» regarding technical exploitation within J2, which requires the formation of a command and control (C2) system for technical exploitation with support for all relevant processes [13].

The specified system should provide [13]:

- coordination and centralized management of all stages of technical exploitation, starting from the collection and identification of collected materials suitable for analysis and ending with the analysis of the obtained results;

- effective interaction between different units and performers;

- rapid dissemination and coordination of information;

- adoption of coordinated decisions and ensuring optimal allocation of resources;

- processing of results in accordance with the priority of tasks and established security protocols;

- increasing the reliability of the classification of collected materials;

- reducing the risks of duplication of efforts or loss of important data (all participants have access to up-to-date information and commanders and analysts can quickly respond to changes in the situation).

Such centralized management should be implemented within a single information space. At the same time, the integration of all source data used in conducting S&TI, TECHINT and TE is proposed to be implemented by using network-centric cognitive IT tools built on the principles of ontology engineering. The ontology structure will allow reflecting specific aspects of the specified information environment by creating information descriptions based on an object-oriented formalization procedure and descriptions of interpretative functions that control the process of supplying an information resource and will also simplify information processing [14].

Also, effective implementation of tasks for conducting scientific and technical expertise of enemy weapons (weapon fragments) is possible through the use of large language models [12] and ontological engineering methodology [15]. At the same time, to ensure the efficiency, reliability and standardization of the analysis process within the framework of S&TI, TECHINT and TE, there is a need to develop an appropriate scientific and methodological apparatus (SMA) for the technical analysis of enemy munitions samples.

The specified SMA should ensure:

- unification of processes, in particular the use of unified approaches to data collection, processing and interpretation;

- increasing the reliability of research by minimizing errors in the process of data collection and analysis;

- implementing transdisciplinary approaches to processing the results of munitions analysis [16];

increasing the efficiency of research by prioritizing tasks and optimizing the expenditure of time, human and material resources.

It is precisely on the development and implementation of the specified SMA that further scientific research will be directed.

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ОРГАНІЗАЦІЙНІ АСПЕКТИ СИСТЕМИ ТЕХНІЧНОЇ РОЗВІДКИ ОЗБРОЄНЬ І ВІЙСЬКОВИХ ТЕХНОЛОГІЙ У КРАЇНАХ НАТО

Вивчення та науково-технічний аналіз зразків (фрагментів) озброєння та військової техніки противника є невід'ємною частиною підтримки обороноздатності держави та є критично важливим для ефективної оборони і стримування в сучасних умовах. В статті розглянуто організацію систем науково-технічної та технічної розвідок, технічної експлуатації країн НАТО, а також проведено аналіз підходів до проведення таких досліджень. Показано мету кожного з процесів, їх складові та результати, які мають бути отримані.

Встановлено, що ключовим фактором, який впливає на ефективність виконання завдань S&TI, TECHINT і TE, є координація дій персоналу, груп і підрозділів, що потребує формування системи управління технічної експлуатації з підтримкою всіх відповідних процесів. Наведено типовий перелік та зміст звітів, які формуються за результатами проведення відповідних досліджень.

Визначено, що в сучасних умовах ефективно впровадження в Україні підходів НАТО до науково-технічного аналізу зразків (фрагментів) ОБТ противника потребує розробки відповідного науково-методичного апарату проведення досліджень. Показано, що результати досліджень мають критичне значення для забезпечення національної безпеки, технологічного лідерства та конкурентоспроможності держави, а також для адаптації до швидко змінюваних викликів.

Ключові слова: науково-технічна розвідка (S&TI), технічна розвідка (TECHINT), технічна експлуатація (TE), озброєння та військова техніка

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МЕТОДИКА РОЗРАХУНКУ ДАЛЬНОСТІ ПОЛЬОТУ БОМБИ, ЩО ОБЛАДНАНА КРИЛОМ І ДВИГУНОМ

У статті викладена методика розрахунку дальності польоту бомби, яка оснащена крилом і турбореактивним двигуном. Запропоновано розрахункові залежності для розрахунку дальності польоту бомби з урахуванням підвищення аеродинамічної якості за рахунок оснащення її крилом та встановлення маршового двигуна.

Показано, що встановлення двигуна дозволяє зменшити кут нахилу траєкторії планерування бомби на величину, яка пропорційна відношенню тяги до сили тяжіння бомби.

За допомогою енергетичного методу доказано, що найменша витрата палива для отримання одного і того ж імпульсу тяги двигун доцільно запускати на початковій ділянці польоту, а планерування бомби на максимальну дальність виконувати на найвишній швидкості.

Ключові слова: авіаційна бомба, планерування бомби, траєкторія польоту, аеродинамічна якість, дальність польоту, турбореактивний двигун.

ВСТУП

Україно-російська війна відрізняється від попередніх збройних конфліктів безпрецедентним масовим застосуванням безпілотних літальних апаратів (БпЛА) і керованих авіаційних бомб. Унікальні бойові властивості БпЛА для вирішення задач розвідки, а згодом у якості ударних засобів, досить докладно проаналізовано військовими фахівцями у багатьох публікаціях.

На даний час разом з БпЛА все більш широкого застосування набувають порівняльно нові боєприпаси – крилаті авіаційні бомби (КАБ). Це обумовлено двома причинами: суттєвим підвищенням бойових властивостей засобів ППО та недостатньою дальністю польоту вільнопадаючих бомб у штатній конфігурації [1, 4].

Модернізація по збільшенню дальності польоту некерованих бомб здійснювалася за наступними напрямками:

- установка на бомбу невеликого крила для підвищення її аеродинамічної якості;
- установка на бомбу додаткового двигуна;
- установка на бомбу рульових органів управління і універсального модуля планерування і корекції (УМПК).

УМПК надавалися функції управління траєкторією польоту КАБ з використанням супутникового зв'язку, а також функції стабілізації і задачі покращення стійкості керованості бомби. Таким чином, звичайна бомба перетворювалася у безпілотний керований літальний апарат [2, 3].

Розуміння особливостей функціонування КАБ дозволить обґрунтовано визначати технічні вимоги до такого засобу ураження.

Метою роботи є відпрацювання робочого науково-методичного апарату з оцінювання аеродинамічних характеристик планеруючої бомби, що оснащена, у тому числі маршовим турбореактивним двигуном та вибору оптимальних значень параметрів польоту після відділення від носія.

РЕЗУЛЬТАТИ ДОСЛІДЖЕНЬ

До КАБ висуваються основні вимоги: ударна міць, точність влучання і дальність планерування. Ударна міць КАБ оцінюється величиною тротилового еквівалента, дальність польоту – аеродинамічною якістю, а ефективність застосування – точністю влучання.

Запас енергії бомба отримує від літака-носія в момент її скидання. Цей запас необхідно перетворити у дальність польоту. Як це зробити, йдеться у даному матеріалі.

Некеровані авіаційні бомби попередніх поколінь мали порівняно невелику дальність польоту. При невеликих дальностях штурману було складно здійснити наведення літака і точне прицілювання на ціль. З розвитком засобів навігації та прицільних систем дальність від місця скидання до цілі безперервно збільшувалася, а висота польоту носія під час скидання стала визначатися особливим коридором. Для унеможливлення входу літака-носія в зону дії засобів ППО противника вона має бути або гранично малою, або не нижчою за деяку велику висоту [4].

Звичайна авіаційна бомба відрізняється невеликою величиною аеродинамічної якості (зазвичай у межах 1...2 одиниць). Її збільшення за рахунок вдосконалення аеродинаміки корпусу бомби повністю себе вичерпало. Залишається одна можливість – оснащення бомби крилом.

Між тим, можливості крила обмежені. У складеному положенні воно повинно вписуватися у габарити бомби, тому розмах крила не повинний перевищувати довжину корпусу бомби. Хорда крила також обмежується: при значній хорді крило виступає за обводи корпусу, порушується його профіль і збільшується мідель, що приведе до росту лобового опору бомби та зниженню її аеродинамічної якості. Всі ці недоліки вимагають пошуку інших варіантів.

Альтернативним варіантом крилу є установка на корпус бомби реактивного двигуна з паливним баком. В деяких випадках застосовується комплексний варіант – крило+двигун.

Таким чином, сучасна КАБ – це новітній і ефективний зразок озброєння, який необхідно терміново впроваджувати і вдосконалювати. Розглянемо більш докладно означені варіанти.

Визначення дальності польоту бомби

У сталому планеруванні КАБ лобовий опір X_a врівноважується складовою сили тяжіння $G \sin \theta$, а прямолінійність руху забезпечується рівністю підйомної сили Y_a і складовою $G \cos \theta$ (рис. 1, а):

$$\begin{aligned} X_a &= -G \sin \theta, \\ Y_a &= G \cos \theta, \end{aligned} \quad (1)$$

де θ – кут планування бомби, $G = gm$ – сила тяжіння бомби.

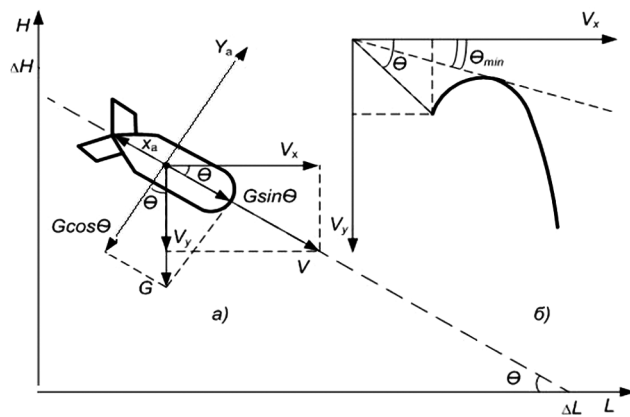


Рис. 1. Схема сил, що діють на бомбу у вертикальній площині

Шляхом ділення даних рівнянь (1) одного на друге одержимо:

$$\operatorname{tg} \theta = -\frac{X_a}{Y_a} = -\frac{C_{xa}}{C_{ya}} = -\frac{1}{K}. \quad (2)$$

Таким чином, кут планування θ визначається однозначно аеродинамічною якістю ЛА K . Найменший кут відповідає максимальній якості.

З приведеного рисунка можна отримати зв'язок між висотою і дальністю планування:

$$\frac{\Delta H}{\Delta L} = -\operatorname{tg} \theta = -\frac{1}{K} \quad \text{або} \quad \Delta L = K \Delta H, \quad (3)$$

де ΔH – витрачена висота за час планерування.

З формули (3) слідує, що максимальну дальність можна одержати при максимальній аеродинамічній якості.

Відомо, що $K_{\max}$ відповідає найвищійшій коефіцієнту підйомної сили $C_{y_{\max}}$ [5, 6]. Найвищійша швидкість, у свою чергу, також відповідає найвищійшій коефіцієнту підйомної сили $C_{y_{\max}}$. При цьому швидкість може бути істинною V , індикаторною V_i або приладовою V_{np} .

Швидкість польоту отримаємо з другого рівняння системи (1) $C_{y_{\max}} V^2 S / 2 = G \cos \theta$. Звідси

$$V_{np} = \sqrt{\frac{2gm}{C_{y_{\max}} \rho_0 S}}. \quad (4)$$

У формулі (4) прийнято $\cos \theta \approx 1$ як для малого кута нахилу траєкторії.

Слід зауважити, що приладова швидкість відрізняється від індикаторної тільки величиною поправок для конкретної системи вимірювання швидкості $V_{np} = V_i - \delta V$, де δV – помилка вимірювання швидкості. Нагадаємо, що індикаторна швидкість однозначно зв'язана з швидкісним напором $q = \rho_0 (V_i)^2 / 2$. У силу малості поправок δV на практиці використовують рівність $V_{np} \approx V_i$.

Перевагою індикаторної і приладової швидкостей є їх незалежність від висоти польоту [6]. При їх обчисленні щільність повітря приймається для нульовій висоті ($\rho_0 = 1,225 \text{ кг/м}^3$).

Якщо $V_{np} = \text{const}$, то швидкісний напір зберігається незмінним. Але при розрахунку дальності польоту необхідно використовувати істинну швидкість (відносно землі) та щільність реальної атмосфери ρ . Зв'язок між істинною та приладовою швидкостями можна записати у виді:

$$V = V_i / \sqrt{\Delta}, \quad V_i = V_{np} + \delta V. \quad (5)$$

Відношення ρ_0 / ρ_H звичайно позначають через Δ , а δV – сумарна поправка до показника швидкості [6]. При зниженні бомби з постійною приладовою швидкістю істинна швидкість буде зменшуватися і на висоті $H = 0$ вони стають рівними.

Визначення максимальної аеродинамічної якості КАБ

Із формули (3) видно, що визначальним параметром дальності польоту КАБ є її аеродинамічна якість. На практиці використовують декілька способів оцінки аеродинамічної якості:

- продувкою моделі КАБ в аеродинамічній трубі;
- розрахунком за діючими методиками;
- льотним експериментом натурної КАБ.

Розглянемо особливості кожного із даних методів.

Для продувки в трубі розробляють продувочну модель КАБ. Вона повинна бути геометрично подібною своєму аналогу.

Модель продувають у трубі і визначають діючі сили і моменти в залежності від кута атаки. За силами і моментами розраховують відповідні коефіцієнти даних сил і моментів $C_x(\alpha)$, $C_y(\alpha)$. Ці залежності моделі і її аналогу повинні бути однаковими. Вони також дозволяють побудувати поляру $C_x(C_y)$.

Приклад такої залежності наведений на рис. 2.

Поляра застосовується для розрахунку багатьох льотних характеристик і, перш за все, лобового опору та аеродинамічної якості. У будь-якій точці поляри можна визначити відношення C_{ya} / C_{xa} , тобто аеродинамічну якість. Максимальну якість можна визначити тангенсом кута нахилу дотичної лінії, що проведена з початку координат до кривої $C_{ya}(C_{xa})$. Точка торкання відповідає найвищійшій коефіцієнту підйомної сили, а саме і максимальній якості [6].

Основною проблемою даного методу є використання досить дорогої аеродинамічної труби.

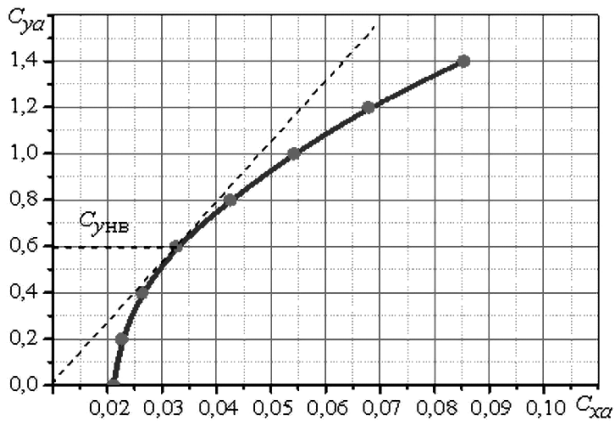


Рис. 2. Приклад поляри КАБ

Розрахункові методи високого рівня з визначення аеродинамічної якості вимагають застосування комп'ютерної техніки та складання складних програм. Найбільш доступним і точним методом визначення аеродинамічних характеристик є льотний експеримент. У ньому в якості моделі може бути використаний безпосередньо сам об'єкт досліджування – КАБ зі штатним вимірювальним обладнанням, що дозволяє реєструвати горизонтальну V_x та вертикальну V_y швидкості польоту, геометричну висоту, кути крену, курсу.

Задачею експерименту є виконання «площадок» з постійним кутом зниження і витримуванням постійної швидкості протягом 10...20 с.

Виконавши такі «площадки» на швидкостях $V_{min}, V_1, V_2, \dots, V_{max}$, будують залежності від швидкості: θ, V_y, K за формулами:

$$\frac{V_y}{V_x} = -\operatorname{tg} \theta = \frac{1}{K} \quad \text{або} \quad V_y = \frac{V_x}{K} \approx \frac{V}{K}. \quad (6)$$

Із рис. 1, б видно, що співвідношення вертикальної і горизонтальної швидкостей також можна знайти через аеродинамічну якість.

Наближена рівність свідчить про те, що горизонтальна складова швидкості V_x є близькою до швидкості по траєкторії V в силу малості кута зниження θ між векторами швидкості. Це дає підставу стверджувати, що в прямолінійному сталому зниженні вертикальна швидкість у K разів менша траєкторної швидкості. Використовуючи цю властивість, можна побудувати поляру швидкостей (рис. 1, б). Дотична до неї визначить мінімальний кут зниження і найвигідніший режим польоту. Звідси вертикальну швидкість можна знайти як $V_y = V/K$.

Максимальна аеродинамічна якість бомби з крилом дозволяє визначити її максимальну дальність польоту.

Оцінка впливу тяги двигуна на дальність польоту бомби

При наявності двигуна на бомбу діє додаткова сила P та додаткова сила ΔG_{cy} – сила тяжіння силової установки і палива для двигуна [7]. Тобто сила тяжіння бомби з двигуном зростає до $G_{\partial\partial} = G + \Delta G_{cy}$. Тоді перше рівняння системи (1) приймає вид:

$$X_a = P - G_{\partial\partial} \sin \theta_{\partial\partial}, \quad (7)$$

де $\theta_{\partial\partial}$ – кут зниження бомби з працюючим двигуном.

Рівняння (2) після установки двигуна приймає вид:

$$Y_a = G_{\partial\partial} \cos \theta_{\partial\partial}. \quad (8)$$

Поділивши (7) на (8), одержимо

$$\frac{1}{K} = \frac{P - G_{\partial\partial} \sin \theta_{\partial\partial}}{G_{\partial\partial} \cos \theta_{\partial\partial}} = \frac{P}{G_{\partial\partial} \cos \theta_{\partial\partial}} - \operatorname{tg} \theta_{\partial\partial}. \quad (9)$$

З порівняння (9) і (2) приходимо до висновку, що силова установка підвищує дальність польоту бомби через зменшення кута планерування.

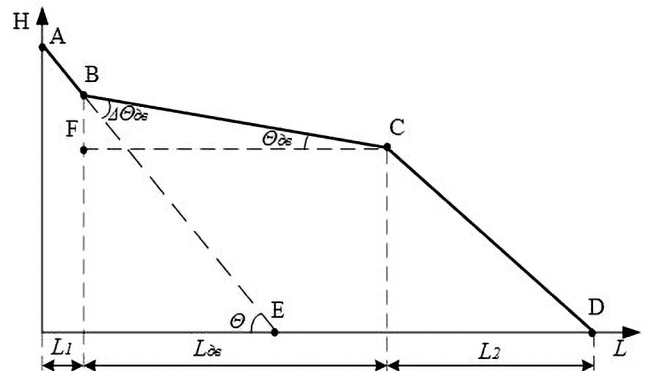


Рис. 3. Траєкторія планерування бомби

Слід зауважити, що зміна конфігурації бомби за рахунок власної тяги та паливного бака декілька підвищує її лобовий опір і зменшує максимальну аеродинамічну якість бомби. Планування виконується на невеликих кутах, тому можна прийняти допущення, що $\cos \Delta \theta_{\partial\partial} \approx 1$ і записати рівняння (9) у виді:

$$\operatorname{tg} \theta_{\partial\partial} = -\left(\frac{1}{K} - \frac{P}{G_{\partial\partial}} \right). \quad (10)$$

По аналогії з формулою (3) дальність польоту бомби з працюючим двигуном можна записати у виді:

$$L_{\partial\partial} = \frac{\Delta H}{\operatorname{tg} \theta_{\partial\partial}}, \quad (11)$$

де ΔH – витрата висоти за час працювання двигуна. При малих кутах допустимо замінювати $\operatorname{tg} \theta$ самим кутом у радіанах. Тоді можна записати $\operatorname{tg} \theta_{\partial\partial} = \theta_{\partial\partial} = \theta - \Delta \theta_{\partial\partial} = 1/K - P/G_{\partial\partial}$. Порівнюючи цю різницю з формулою (8), одержимо:

$$\Delta \theta_{\partial\partial} = P/G_{\partial\partial} \text{ рад} = 57,3 P/G_{\partial\partial} \text{ град}. \quad (12)$$

Приріст дальності польоту за рахунок працюючого двигуна дорівнює:

$$\Delta L_{\partial\partial} = \frac{\Delta H}{\operatorname{tg} \Delta \theta_{\partial\partial}} - \frac{\Delta H}{\operatorname{tg} \theta} = \Delta H \left(\frac{1}{\operatorname{tg} \Delta \theta_{\partial\partial}} - \frac{1}{\operatorname{tg} \theta} \right). \quad (13)$$

Двигун за запасом палива має обмежений час роботи і встає питання, на якій частині траєкторії його потрібно включати: одразу після скидання бомби або наприкінці? Іншими словами, де він надає бомбі найбільшу енергію?

Загальна енергія бомби оцінюється величиною

$$H_e = H + \frac{V^2}{2g}, \quad (14)$$

де H_e – загальна енергія 1 кг ваги бомби або так звана «енергетична висота», що складається з потенційної (H) і кінетичної ($V^2/2g$) енергій.

Приріст енергії за рахунок тяги двигуна можна оцінити у виді:

$$\Delta H_e = \frac{dH_e}{dt} \Delta t. \quad (15)$$

Похідну dH_e/dt визначимо диференціюванням рівняння (15):

$$\frac{dH_e}{dt} = \frac{dH}{dt} + \frac{V}{g} \frac{dV}{dt}. \quad (16)$$

Вона складається з суми похідних геометричної висоти (вертикальної швидкості) і з тангенціального прискорення.

Похідну dH/dt визначимо через параметри бомби. Для цього напишемо два відомих рівняння динаміки польоту для висоти і швидкості:

$$\frac{dH}{dt} = V \sin \theta_{\partial\partial}, \quad \frac{dV}{dt} = g(n_x - \sin \theta_{\partial\partial}). \quad (17)$$

Визначимо з другого рівняння $\sin \theta_{\partial\partial}$

$$\sin \theta_{\partial\partial} = gn_x - \frac{1}{g} \frac{dV}{dt}. \quad (18)$$

та підставимо його у перше рівняння. Отримаємо:

$$\frac{dH}{dt} = V \left(gn_x - \frac{1}{g} \frac{dV}{dt} \right). \quad (19)$$

Підставимо похідну dH/dt в (16) та одержимо:

$$\frac{dH_e}{dt} = Vn_x = V \frac{P - X_a}{G_{\partial\partial}} \quad (20)$$

За знаком похідної dH_e/dt можна визначити зміну функції (у даному разі функції $H_e(t)$): якщо похідна додатна (а це можливо при $P > X_a$), то функція зростає – енергія бомби збільшується за часом незалежно від маневру, що виконує бомба. І навпаки – якщо тяга менша за лобового опору, загальна енергія зменшується за часом.

У нашому випадку звичайно $P < X_a$, тому тяга двигуна тільки зменшує похідну dH_e/dt , але не змінює її знак. Іншими словами, і з тягою двигуна енергія бомби продовжує зменшуватися, але не так швидко як без двигуна.

Дальність польоту при наявності двигуна визначається рівнянням:

$$\frac{dL}{dt} = V \cos \theta_{\partial\partial}. \quad (21)$$

Поділивши дане рівняння на рівняння (20), одержимо:

$$\frac{dL}{dH_e} = \frac{\cos \theta_{\partial\partial}}{n_x}. \quad (22)$$

Шляхом інтегрування (20) одержимо:

$$L = \int_{H_{e1}}^{H_{e2}} \frac{\cos \theta_{\partial\partial}}{n_x} dH_e. \quad (23)$$

У формулі (21) $H_{e1} = H_1 + \frac{V_1^2}{2g}$, $H_{e2} = H_2 + \frac{V_2^2}{2g}$ де

індекс «1» – відповідає польоту бомби у момент включення двигуна, індекс «2» – моменту закінчення його роботи. Вважаємо, що включення двигуна змінює тільки кут нахилу траєкторії і величину тангенціального перевантаження від θ і n_x до значень $\theta_{\partial\partial}$ і $n_{x\partial\partial}$. Їх постійність дозволяє записати рішення інтегралу (21) у наступному виді:

$$L_{\partial\partial} = \frac{\cos \theta_{\partial\partial}}{n_{x\partial\partial}} (H_{e2} - H_{e1}). \quad (24)$$

Таким чином, частина траєкторії польоту бомби з працюючим двигуном обумовлена двома параметрами: $\theta_{\partial\partial}$ і $n_{x\partial\partial}$ та приростом енергії.

Із формули (18) видно, що приріст енергії бомби тільки за рахунок тяги двигуна буде залежати від величини тяги P , часу роботи двигуна Δt , а також від швидкості польоту:

$$\Delta H_{e\partial\partial} = \frac{VP}{G} \Delta t. \quad (25)$$

Раніше було показано, що зниження бомби доцільно виконувати на постійній *приладовій* швидкості, яка забезпечує максимальну аеродинамічну якість [3]. Між тим приріст енергії в формулі (23) визначається *істинною* швидкістю. Ці швидкості пов'язані між собою умовою $V \approx V_{\text{пр}} \sqrt{\Delta}$, тобто при плануванні бомби з постійною приладовою швидкістю істинна швидкість і приріст енергії будуть зменшуватися по мірі зменшення висоти.

Так, на висоті $H = 12\,000$ м маємо $\sqrt{\Delta} = 0,5$, на висоті $H = 8\,000$ м $\sqrt{\Delta} = 0,65$, на висоті $H = 5\,000$ м він дорівнює $\sqrt{\Delta} = 0,77$, біля землі $\sqrt{\Delta} = 1$.

Звідси слідє висновок: включення двигуна доцільно виконувати на початку траєкторії планування, коли істинна швидкість найбільша, а двигун забезпечує найбільший приріст дальності. Рух бомби після скидання буде залежати від закону управління бомби. Найбільш раціональним, на нашу думку, є закон управління швидкістю. Витримування приладової швидкості найвигідніше забезпечить зниження бомби з максимальною аеродинамічною якістю і, отже, найбільшу дальність.

Тому перед скиданням бомби рулі повинні бути встановлені в положення, що відповідає їх балансувальній величині на найвигіднішій швидкості і висоті, а також з включеним двигуном. Тоді бомба після відділення від літака у перехідному процесі буде намагатися перейти на найвигіднішу швидкість і збалансуватися по моментах та силах.

Так, для отримання найбільшої дальності польоту скидання бажано виконувати якомога на більшій швидкості і висоті, щоб бомба набула найбільшу енергію (формула 14), яку можливо перетворити в дальність. У цьому випадку система керування буде намагатися зменшити швидкість шляхом зменшення кута зниження бомби або переводу її в режим набору висоти [8]. На даному етапі включається двигун.

Після досягнення найвигіднішої швидкості система керування переведе бомбу в режим сталого зниження (точка B на рис. 3). Після витрати палива двигун зу-

пинається, бомба переходить на більший кут зниження (точка С).

Таким чином, загальна дальність польоту бомби буде рівною:

$$L = L_1 + L_{\text{де}} + L_2, \quad (26)$$

де L_1 – ділянка польоту від початку скидання до досягнення найвигіднішої швидкості, $L_{\text{де}}$ – ділянка польоту з працюючим двигуном, L_2 – ділянка польоту після виключення двигуна.

ВИСНОВКИ

Проведено аналіз зміни траєкторії польоту бомби за рахунок роботи реактивного двигуна. Показано роль двигуна у забезпеченні зменшення кута нахилу траєкторії планерування бомби.

Показано, що оптимальним режимом польоту як з включеним, так і з виключним двигуном є найвигідніша приладова швидкість.

За допомогою енергетичного метода динаміки польоту встановлено, що включення двигуна доцільно виконувати одразу після скидання перед виходом на режим сталого планерування.

Визначені умови забезпечення максимальної дальності польоту КАБ.

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**METHODOLOGY FOR CALCULATING THE
FLIGHT RANGE OF A BOMB EQUIPPED WITH
WINGS AND AN ENGINE**

The article presents a methodology for calculating the maximum flight range of a bomb equipped with wings and a turbojet engine. Working formulas are derived for calculating the bomb's flight range, taking into account the improvement of its aerodynamic efficiency due to the addition of a gliding module and the installation of a cruise engine.

A methodology is proposed for determining the main aerodynamic characteristics of a gliding bomb and constructing its polar diagram based on the results of a flight experiment with a model. An assessment is made of the impact of engine thrust on the bomb's flight range. It is shown that installing an engine reduces the gliding trajectory angle of the bomb by a value proportional to the ratio of thrust to the bomb's weight. Calculation dependencies are proposed to determine the optimal moment for starting the cruise engine after the bomb is released from the carrier.

Using the energy method, it is proven that the lowest fuel consumption for obtaining the same thrust impulse is achieved when the engine is started at the initial phase of the flight, while the bomb's gliding for maximum range should be performed at the most advantageous indicated airspeed. The conditions for achieving the maximum flight range of the bomb are determined. Calculation dependencies are provided for determining the maximum range, taking into account all phases of the bomb's flight.

Keywords: aerial bomb, bomb gliding, flight trajectory, aerodynamic efficiency, flight range, turbojet engine.

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DESIGN AND FUNCTIONAL FEATURES OF THE SMALL-SIZED ANTENNA ARRAY «COMETA-M»

In the article, the results of research on the design and functional characteristics of «Cometa-M» are presented. It is a compact adaptive antenna array with an integrated satellite navigation receiver, which is actively used by the enemy against Ukraine as a key component of the navigation system for unmanned aerial vehicles and other aerial attack means.

The technical specifications and operational features of «Cometa-M» have been investigated. During the research, the construction structure and the purpose of its key components were determined. Based on the research results, a structural diagram was compiled and the operating principles of «Cometa-M» were described.

Keywords: DAA, antenna array, anti-jamming, beam pattern, navigation system, CRPA, GNSS, Cometa-M, UAV.

INTRODUCTION

A key element of various types of UAVs, ballistic and cruise missiles, which are widely used in the armies of many countries, are satellite navigation systems (SNS). It should be noted that special systems for protecting the respective GNSS from active interference have recently been created exclusively on the basis of digital antenna arrays (DAA) with the implementation of adaptive signal reception algorithms [1]. The main feature of DAA, as is known [1–13], is that they are able to actively change the shape of their radiation pattern to reduce the impact of interference from electronic warfare (EW). Due to digital signal processing, such an antenna array can adaptively reduce the level of interfering signals, which makes it effective for operation in complex electromagnetic environments.

Given the small number of antenna elements, the interference immunity of the DAA in on-board SNS largely depends on their technical characteristics and functional capabilities to counteract interference while maintaining the required quality of reception of useful signals.

The Russian Federation pays great attention to the development of electronic countermeasures against interference

with on-board satellite navigation systems «Cometa-M», which use small-sized DAAs. This approach has been implemented in the Orlan-10 UAV, Shahed-136 (Geran-2) strike UAVs, and the UMPK (Universal Module Planning and Correction) of guided aerial bombs.

The purpose of the article is to perform a detailed analysis of the technical design and functional features of the «Cometa-M» SNA modules for further determination of their properties and interference resistance.

ANALYSIS OF KEY RESEARCH AND PUBLICATIONS

The analysis of the main publications on the study of designs and features of the use of digital charting technology to ensure the interference immunity of satellite navigation systems, given in [1], was a pioneering work in this area in the former USSR. Over the past 10 years, there has been a widespread introduction of DAAs into satellite navigation systems, accompanied by a significant number of scientific papers and publications of foreign origin on the practical implementation of SNS signal processing in such antenna arrays. In addition to those mentioned in [1], we can mention, for example, articles [14–16]. The term CRPA (Controlled Reception Pattern Antenna) is most often used in the context of using DAA for navigation systems, which was introduced by developers solely as a marketing step to create the illusion of having something original in their developments. In fact, CRPA is a typical receiving DAA, which uses long-known methods of signal processing and formation of zeros in the directional pattern in the directions of interference. Such CRPAs have become widespread in radar, hydroacoustics, ultrasound diagnostics and communication systems [2–13]. For example, at Stanford University, a DAA with the ability to direct the beam and adaptively generate zeros was considered as a CRPA, which is presented in [14]. Studies have been conducted on the impact of GPS receiver architecture on the operation of CRPAs. The impact of different receiver architectures on signal quality and interference suppression efficiency was assessed. The influence of the sequence of operations for generating the signal pattern and correlation, the number of quantisation levels and the dynamic range of ADCs (analogue-to-digital converters) was analysed.

Taking into account the different features of carriers in onboard SNSs, both 4 and more antenna elements are used to create a CRPA. Paper [15] presents the development and testing of a 7-element controlled radiation pattern antenna (S-CRPA) with a diameter of 7 inches. An approach using special materials was applied, which allows reducing the physical dimensions of the antenna system without losing phase characteristics. The article presents test results that demonstrate the effectiveness of the corresponding CRPA in suppressing interference and ensuring reliable reception of GPS signals.

Considerable attention is also paid to the algorithms and methods used to process GPS, GLONASS, Galileo, Beidou signals in the DAA SNS. Article [16] discusses methods of forming «zeros» and «rays» of the radiation pattern of the antenna array of navigation equipment. These methods are aimed at suppressing signals from powerful

point sources of interference and increasing the sensitivity of receiving equipment. Additional methods of filtering and suppression of in-band narrowband interference are also considered [17].

According to the results of the analysis of publications, it should be noted that they consider new methods and approaches to the creation of various types of DAA/CRPA, improvement of GNSS receivers' performance characteristics aimed at ensuring the SNS interference protection.

RESEARCH RESULTS

The analysis of the structure and design features of the «Cometa-M» product indicates its high constructive manufacturability. It should be noted that with rather small dimensions of 100 mm x 100 mm x 30 mm (LxWxH), the product managed to implement a 4-channel DAA, which is capable of adaptively changing the antenna pattern depending on the existing interference. At the same time, the «Cometa-M» module contains a GNSS receiver integrated into its design. That is, this product provides a solution to the navigation task of determining the location with an accuracy that depends on the GNSS receiver used and spatial-frequency filtering of interference signals.

Let's consider the design and main elements that make up a typical version of the «Cometa-M» device used in 2022 as part of the Orlan-10 UAV. The appearance of the main signal processing board with the designation of the main elements is shown in Figs. 1, 2.

Structurally, all elements of the «Cometa-M», except for the patch antennas, are placed on a single board with a high density of filling on both sides. On one side, there are Altera Cyclone V FPGAs [18], a PRO-04 navigation receiver [19], LTC5541 RF mixers [20] and ADL5561 differential amplifiers [21], LTC2174 UKG-14 14-bit 4-channel analogue-to-digital converter (ADC) [22], AD9517-4ABCPZ clock generator with 12 outputs [23],

MAATSS0018 10dB digital attenuators [24], and ADT7310 16-bit precision temperature sensor.

The backside of the board contains an 8 Mbyte EPCQ64A flash memory [25], an integrated frequency synthesiser and an ADF4360-4 oscillator [26], a high-speed single-channel TxDAC AD9755 [27] with two multiplexed 14-bit ports, an active LT5560 mixer [28], bandpass filters P4 and P14, a low-noise DC/DC converter LTM4613V [29] with an input voltage of 5V – 36V and current up to 8A, 3-output low-voltage DC/DC voltage regulator LTM4615V [30].

Taking into account the complexity of the device and the multilayer topology of the board, to determine the capabilities and principles of functioning of this module, an important part of the research is to determine the characteristics of the main elements and study their interaction. The defined technical characteristics of the main components are shown in Table 1.

The research was hampered by a lack of information about the characteristics of specific components that are extremely difficult to identify, but nevertheless affect signal processing. For example, after the signal is received from the antenna elements, each receiving channel is frequency selected using a bandpass filter. Since the characteristics of the P4 and P14 filters are unknown, they were determined by measurements using the NanoVNA portable vector network analyser and NanoVNA Server 0.6.2 software. The results of the measurements, namely the scattering parameters (S-parameters S11 (reflection coefficient) and S21 (transmission coefficient)), as well as the SWR of the filters are shown in Figs. 3 – 6.

According to the results of the measurements, the central frequency of the filter marked «P 4» is 1608 MHz, the bandwidth is 74.9 MHz (-3 dB level), and the maximum transmission coefficient is - 3.25 dB at a frequency 1609.4 MHz. For the filter marked «P 14», respectively,

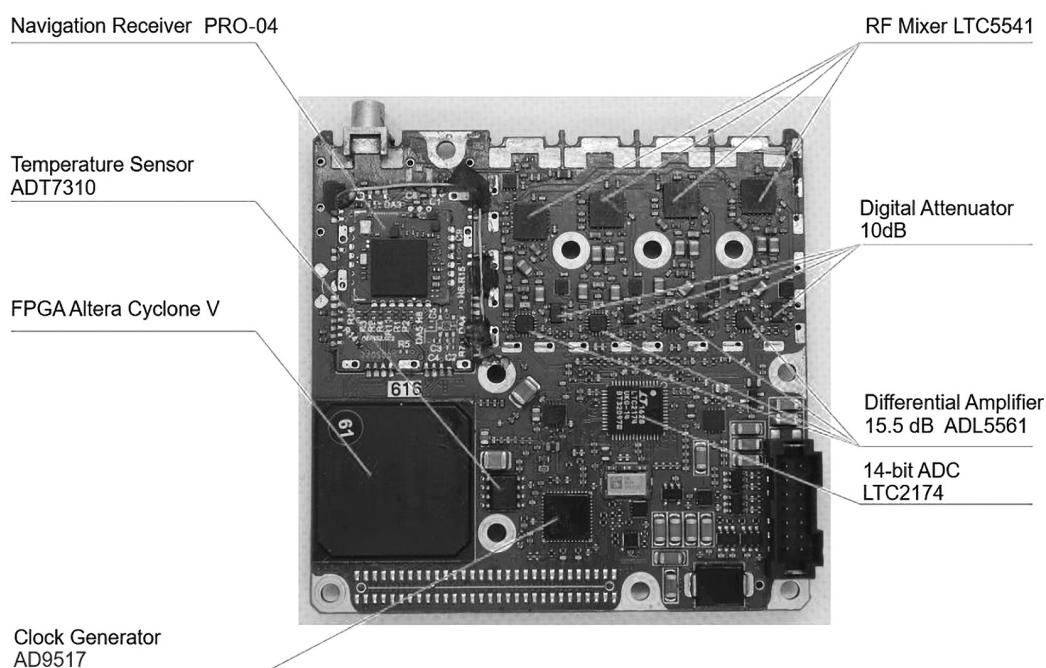


Fig. 1. View of the signal processing board with the main elements

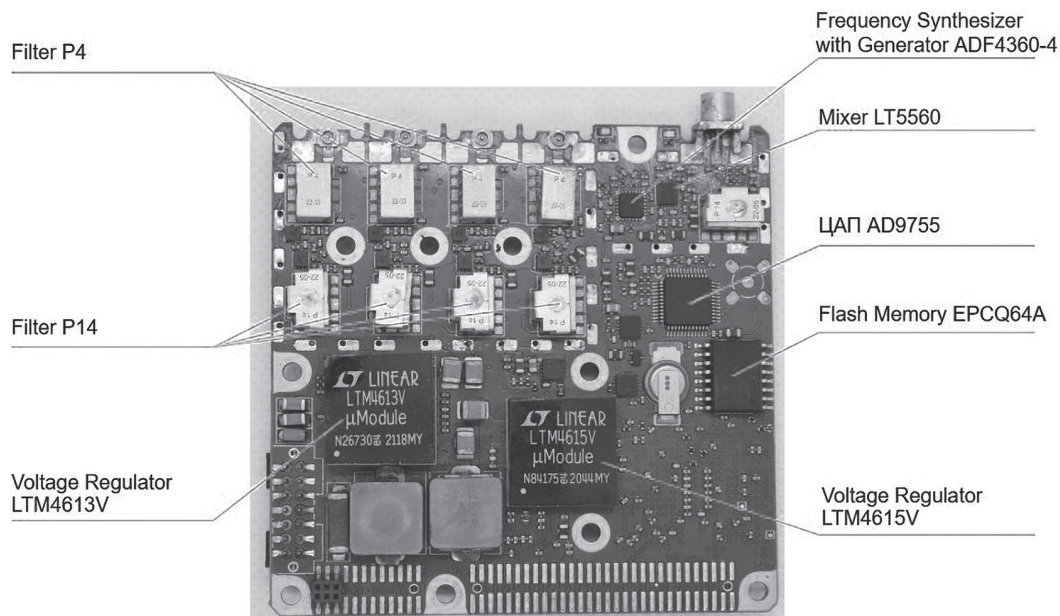


Fig. 2. View of the signal processing board (back side) with the main elements marked

Table 1. Technical characteristics of the main components of the «Cometa-M»

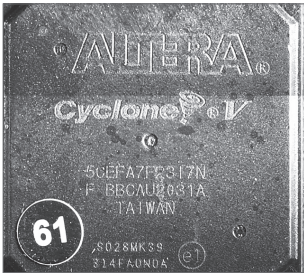
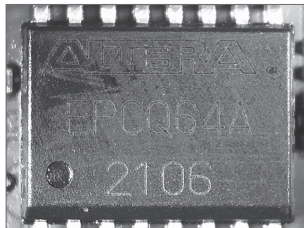
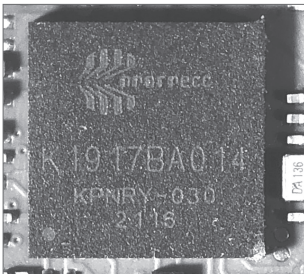
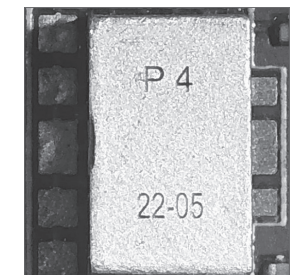
No.	Image	Description
1		ALTERA Cyclone V 5CEFA7F23I7N F BBCAU2031A TAIWAN S028MK39 314FA0N0A Programmable logic integrated circuit (PLIC) Number of logical elements: 149,500; number of adaptive logic modules (ALMs): 56,480; built-in memory: 7.696 Mbit I/O ports: 240. maximum operating frequency: 925 MHz supply voltage: 1.1B Operating temperature: -40°C to +100°C housing: 484-ball Fine-Pitch Ball Grid Array (FBGA)
2		ALTERA EPCQ64A 2106 The EPCQ64A flash memory is used to store configuration data for the FPGA Capacity: 64 Mbit (8 Mbyte) Interface: SPI, Dual SPI and Quad SPI Supply voltage: 2.7 V to 3.6 V
3		K1917BA014 KPNRY-030 2116 The PRO-04 GNSS receiver is a navigation device developed in Russia by «NIIMA Progress» System support: GLONASS, GPS and Galileo Coordinate determination time: 27 s for cold start, 25 s for warm start, 2 s for hot start and 1 s for recapture, Sensitivity: -145 dBmW in search mode and -161 dBmW in tracking mode. Operating temperature: -40 °C to 85 °C
4		Bandpass filter P4 central frequency 1608 MHz 75 MHz bandwidth (at -3 dB level)

Table 1. (continued)

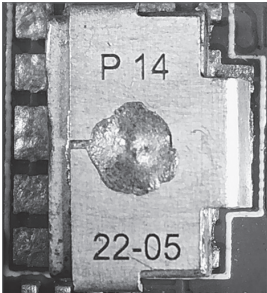
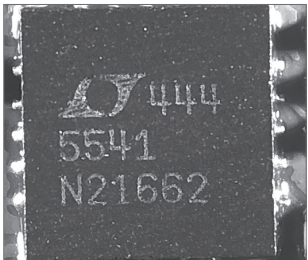
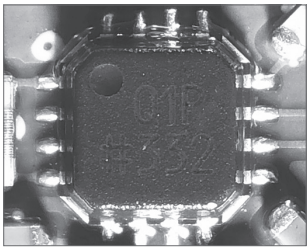
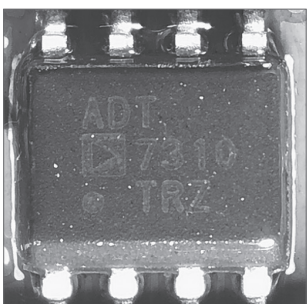
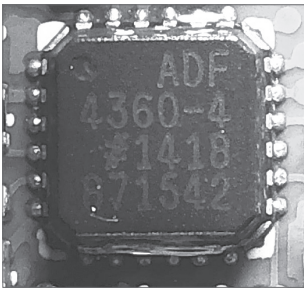
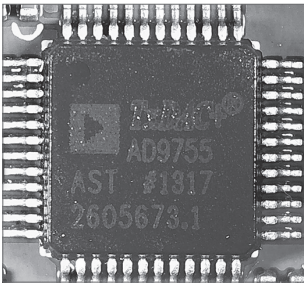
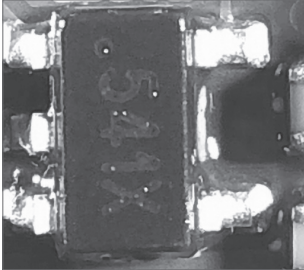
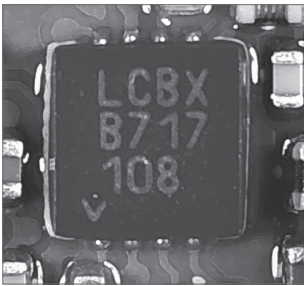
No.	Image	Description
5		Bandpass filter P14 central frequency 1590 MHz 53 MHz bandwidth (at -3 dB level)
6		444 5541 N21662 LTC5541 radio frequency mixer with frequency reduction for the range from 1.3 GHz to 2.3 GHz Gain: 7.8 dB Noise figure (NF) 16 dB for blocking signal up to +5 dB. Case type: 20pin QFN. Operating temperature: -40 °C to 85 °C
7		Q1P #332 Differential amplifier ADL5561 Fixed gain: 6 dB, 12 dB or 15.5 dB Low noise and distortion levels Used as a driver for high-speed ADCs from 8 to 16 bits Case type: LFCSP-16 Operating temperature: -40 °C to 85 °C
8		1628 LTC2174 UKG-14 BT32097 e3 14-bit analogue-to-digital converter (ADC) number of inputs for simultaneous digitisation - 4; sample rate - up to 105 MSPS; data interface - LVDS serial; supply voltage 1.7V-1.9V; operating temperature from -40 °C to +85 °C
9		ADT 7310 TRZ ADT7310 precision 16-bit digital temperature sensor with SPI interface, accuracy ± 0.5 °C operating temperature: from -55 °C to +150 °C
10		AD9517-4 ABCPZ #2136 5479133.1 SINGAPORE AD9517-4ABCPZ clock generator with 12 outputs and built-in voltage controlled oscillator (VCO), with a frequency range from 1.45 GHz to 1.80 GHz. One differential or two single-pole input signals. Input: LVPECL, LVDS or CMOS signals, Output: LVPECL with a frequency of 1.6 GHz, two pairs of 800 MHz LVDS outputs. Operating temperature: -40 °C to +85 °C Case type: 48 pin LFCSP

Table 1. (continued)

No.	Image	Description
11		ADF4360-4 #1418 871542 Integrated frequency synthesiser and oscillator ADF4360-4 Provides a high level of stability and accuracy of generated signals Output frequency range: 1450 MHz to 1750 MHz. It has the ability to divide the output frequency by 2, which allows you to get frequencies in the range from 725 MHz to 875 MHz. Power supply from 3.0 V to 3.6 V. Programmable output power level and dual-module 8/9, 16/17, 32/33 pre-divider for precise frequency selection. Three-wire serial interface. Operating temperature from -40 °C to +85 °C
12		TxDAC AD9755 AST #1317 2605673.1 High-speed single-channel DAC with two multiplexed ports; Bit depth –14 bits. Up to 300 MSPS update speed; high level of signal purity; built-in PLL to double the clock frequency; 3.0 V to 3.6 V power supply; Case type: 48-pin LQFP
13		541X MAATSS0018 10dB digital attenuator for frequencies up to 2GHz Maximum power for 500 – 2000 MHz: +34 dBm Operating temperature: from -40 C° to +85 C°
14		LCBX B717 108 LT5560 high performance broadband (0.01MHz to 4GHz) active mixer Gain of 2.4 dB Power supply: 2.7 V to 5 V Case type: 3×3mm DFN
15		LTM4613V Ultra low noise DC/DC converter Input voltage: 5V – 36V; Output voltage: 3.3V – 15V (adjustable with an external resistor); Output current: up to 8A Case type: LGA-133 (15mm × 15mm × 4.32mm) Operating temperature: -40 °C to +125 °C
16		LTM4615V three-output low-voltage DC/DC voltage regulator, includes overvoltage protection, overcurrent protection, thermal shutdown, programmable soft start function Input voltage: 2.375 V – 5.5 V for DC/DC converters and 1.14 V – 3.5 V for VLDOs (very low voltage drop). Output voltage: 0.8 V – 5 V for two DC/DC converters, each with an output current of up to 4A, and 0.4 V – 2.6 V for VLDO with an output current of up to 1.5 A. Case type: LGA-133 (15mm × 15mm × 4.32mm) Operating temperature: -40 °C to +125 °C

the central frequency of 1590 MHz, the passband 53 MHz (-3 dB level), and the maximum transmission coefficient level -4.9 dB at a frequency 1580 MHz were obtained.

It should be noted that according to the bandwidth measurements, the «P4» and «P14» filters are highly specialised and designed to filter signals from global navigation systems in the L1 range of GPS, GLONASS, and Galileo.

At the same time, it is worth noting that these filters are much less suitable for use with the Beidou navigation system, which has a centre frequency 1561 MHz. According to the defined frequency characteristics, the filters will introduce additional attenuation for a signal of more than 3 dB, since the Beidou operating band is outside the filter's passband at -3 dB. This device has a built-in PRO-04 GNSS receiver that does not support data acquisition from the Beidou system, so the use of filters with these characteristics is quite natural, but the «Cometa-M» design is designed to be used with different GNSS receivers, given the prepared space for mounting the receiver board on the «Cometa-M» main board. This fact is confirmed by studies of other «Cometa-M» samples produced later, as subsequent versions use a wider operating range and other Beidou-enabled receivers.

Center frequency:	1.60851GHz
Bandwidth (-3 dB):	74.9422MHz
Quality factor:	21.46
Bandwidth (-6 dB):	108.947MHz
Lower side:	
Cutoff frequency:	1.57148GHz (-6.3 dB)
-6 dB point:	1.55299GHz (-9.3 dB)
-60 dB point:	707.515MHz (nan dB)
Roll-off:	136.037dB/octave
Roll-off:	451.905dB/decade
Upper side:	
Cutoff frequency:	1.64642GHz (-6.3 dB)
-6 dB point:	1.66193GHz (-9.3 dB)
-60 dB point:	2.00000GHz (-inf dB)
Roll-off:	220.652dB/octave
Roll-off:	732.989dB/decade

Fig. 4. The results of the analysis of the filter parameters marked «P 4», obtained using NanoVNA Server 0.6.2 software

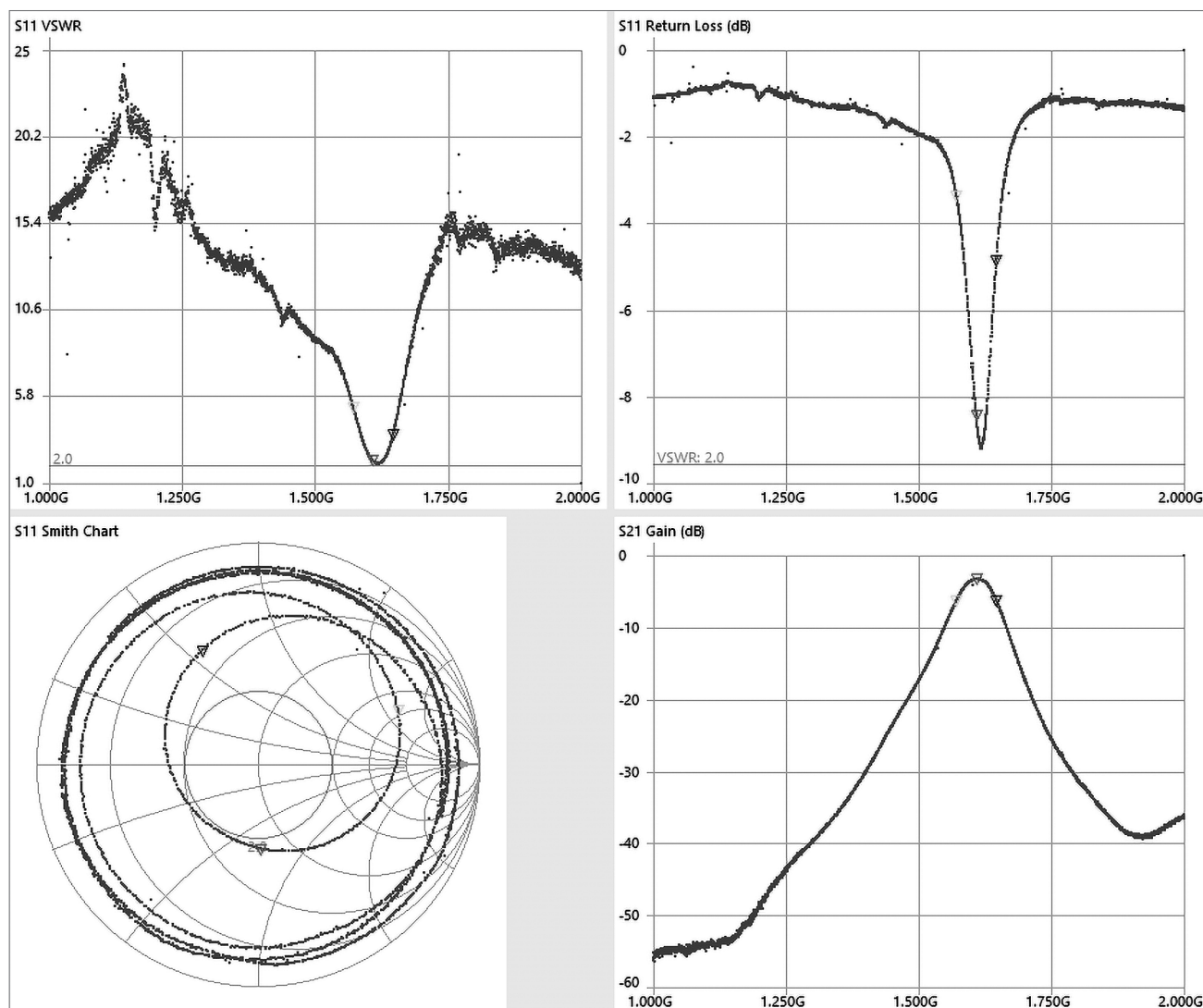


Fig. 3. Measurement results of the frequency characteristics of the filter marked «P 4»

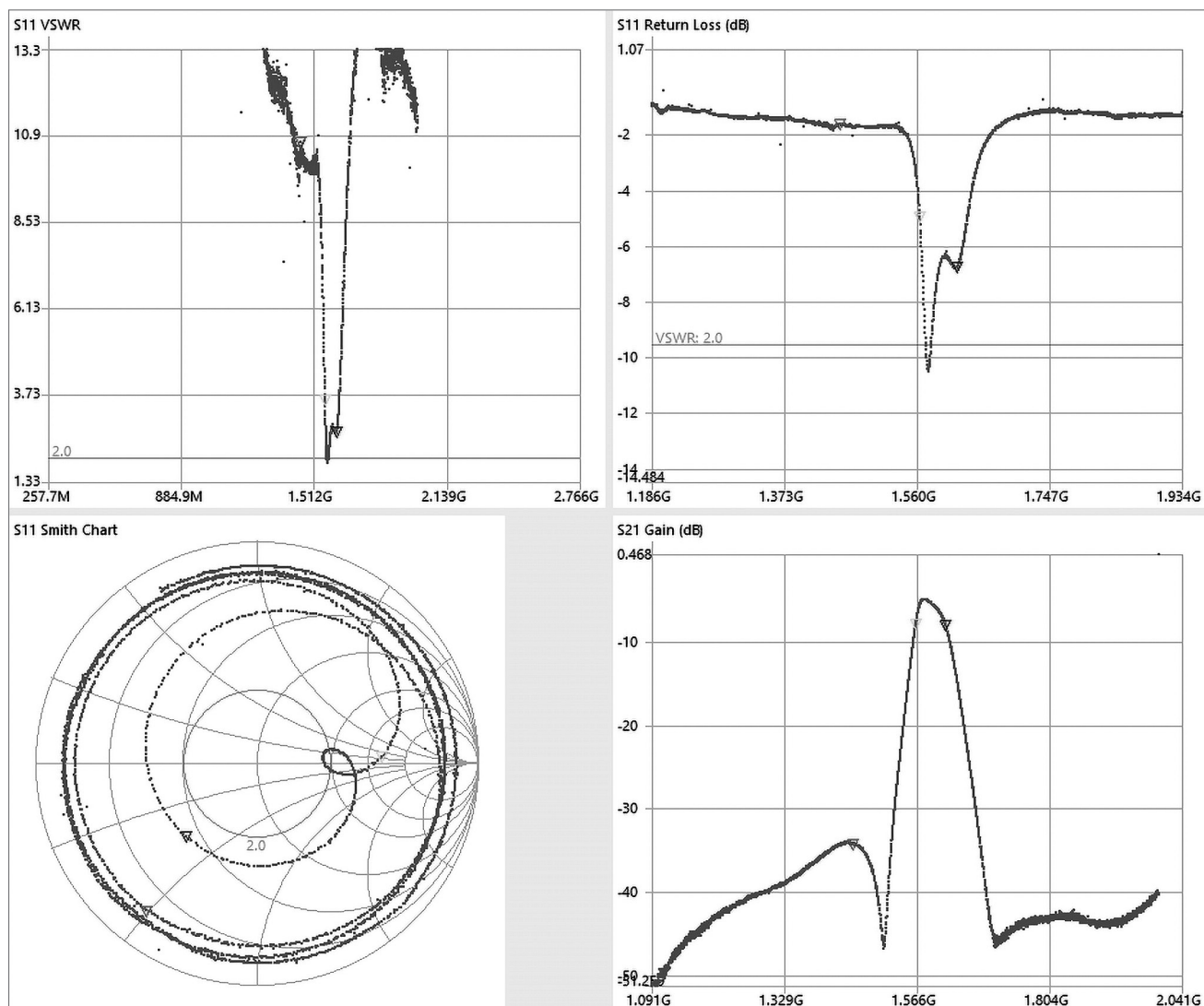


Fig. 5. Measurement results of the filter parameters marked «P 14»

Center frequency:	1.59024GHz
Bandwidth (-3 dB):	53.1529MHz
Quality factor:	29.92
Bandwidth (-6 dB):	70.6504MHz
Lower side:	
Cutoff frequency:	1.56388GHz (-8.0 dB)
-6 dB point:	1.55761GHz (-11.1 dB)
-60 dB point:	1.33138GHz (nan dB)
Roll-off:	646.080dB/octave
Roll-off:	2146.233dB/decade
Upper side:	
Cutoff frequency:	1.61704GHz (-8.0 dB)
-6 dB point:	1.62826GHz (-11.0 dB)
-60 dB point:	2.00000GHz (-inf dB)
Roll-off:	515.895dB/octave
Roll-off:	1713.767dB/decade

Fig. 6. The results of the analysis of the filter parameters marked «P 14», obtained using NanoVNA Server 0.6.2 software

For a more detailed assessment of the frequency characteristics of the SNS device, the bandwidth of the input circuit «antenna – bandpass filter – amplifier – bandpass filter» was measured, which directly sets the limits of the operating range of the «Cometa-M». Fig. 7 shows the results of the bandwidth measurements, according to which the resulting centre frequency for the specified circuit was 1589.59 MHz with a bandwidth 55.48 MHz at the -3 dB level. At the centre frequency, the maximum level of the transmission coefficient was 4.9 dB, which indicates that the signal is amplified by the LNA (Low Noise Amplifier).

Taking into account the topology of the signal processing board of the «Cometa-M» device, the characteristics of these components, their interconnections, the manufacturer's recommendations for the use of components and the analysis of typical approaches to building the architecture of the DAC [1–13], a simplified block diagram of the device is shown in Fig. 8.

According to the scheme shown in Fig. 8, the high-frequency payload satellite signal, along with possible interference, is received by 4 patch antennas combined into an antenna unit on a single board. Each of the antenna

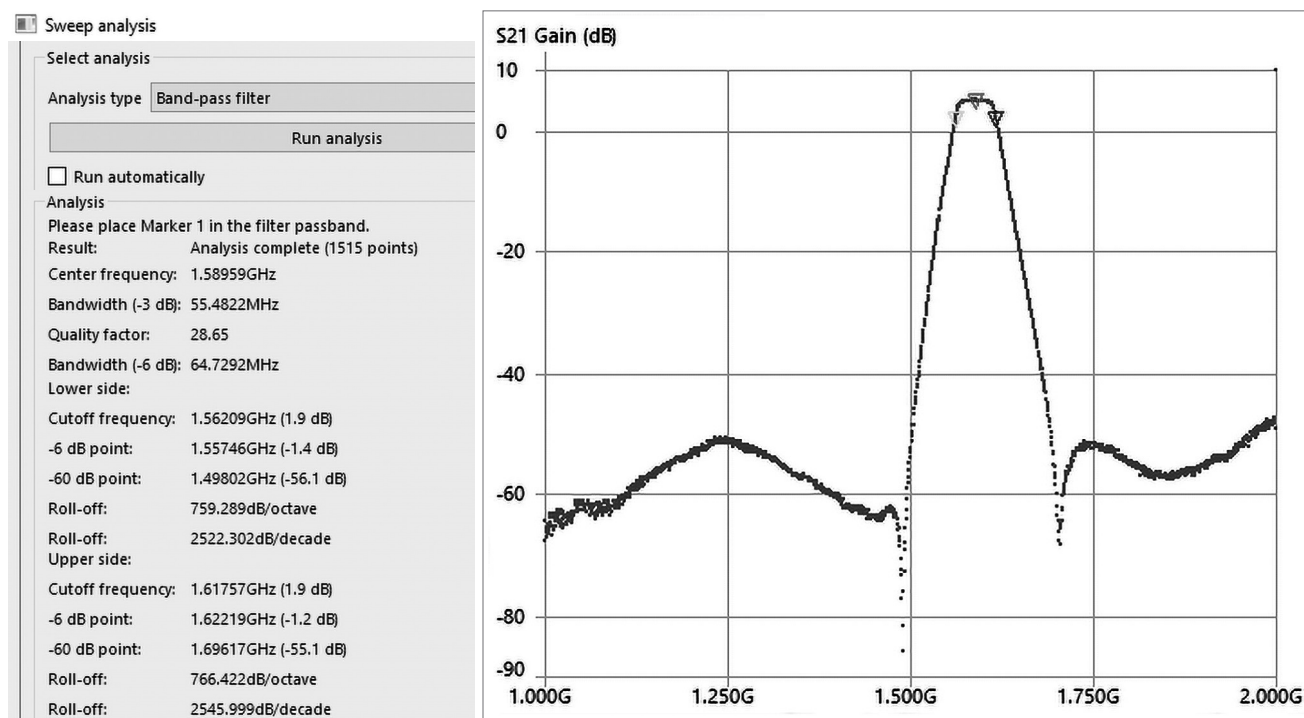


Fig. 7. The results of the analysis of the frequency response of the receiving channel segment consisting of an antenna element, a bandpass filter, and a frequency-selective amplifier

elements has a separate output, which is connected to a bandpass filter via a high-frequency cable. The received signal is then amplified using a low-noise amplifier (LNA) and passed through a bandpass filter again. The filters cut out unwanted frequencies and select only the desired frequency range where the useful signal is to be found. This eliminates noise and interference from other signals. The ATT digital attenuators in each of the 4 receiving channels adjust the signal level to reduce its power by 10 dB to prevent mixer overload, but the attenuator control mode is single-bit, i.e. the specified 10 dB attenuation can be enabled or disabled.

The mixer converts the frequency to a much lower frequency – the intermediate frequency (IF). The intermediate frequency signal is amplified using an ADL5561 differential amplifier with a controlled gain (VGA), which amplifies the IF signal to the required level. The signal is then digitised using a 14-bit LTC2174 analogue-to-digital converter and sent via a high-speed LVDS interface to an ALTERA FPGA, which processes the digital data, performs digital signal processing (DSP) algorithms and zeroing when interference is detected. The processed digital signal is fed to the AD9755 high-speed 14-bit digital-to-analogue converter, which converts the digital signal to analogue. This component is used to generate a high-quality analogue signal with high accuracy and linearity from the digital data stream. The LT5560 high-frequency active mixer is used to convert the frequency of the signal. It mixes the analogue signal with a local oscillator (LO) signal to produce a new, significantly higher frequency.

The ADF4360-4 integrated voltage-controlled oscillator (VCO) frequency synthesiser is used to generate a stable local oscillator (LO) signal. The frequency of the LO signal can be precisely tuned using a phase locked loop (PLL),

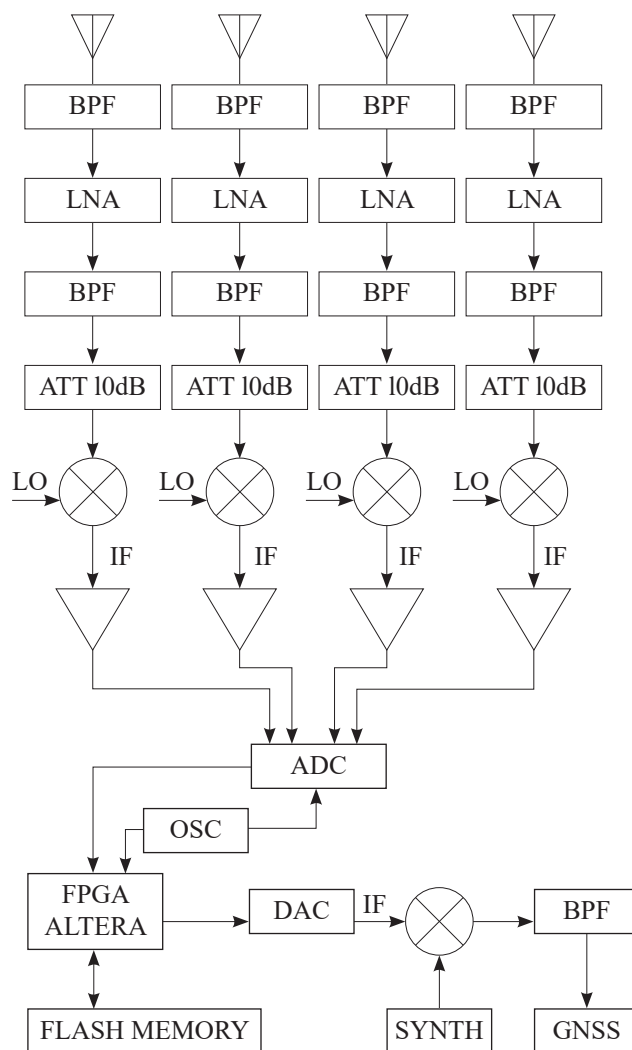


Fig. 8. Block diagram of the «Cometa-M» device

providing high stability and accuracy. The received high-frequency signal from the mixer is fed through a band-pass filter (BPF) to the PRO-04 GNSS receiver, where the satellite signal is processed and navigation messages are demodulated. The resulting navigation solution with defined coordinates, altitude, etc. is transferred in the form of digital data to the FPGA (PLIC), where it can be further processed and sent to the output connector of the device as the resultant data.

Taking into account the components used in the implementation of this device, their characteristics, structural scheme, as well as the approaches used in the formation of the adaptive radiation pattern, it can be argued that the following algorithm is implemented in the «Cometa-M» device.

1. The signal is received independently by each of the patch antennas, followed by filtering and amplification of signals in a certain frequency range.
2. The signals are digitised by a 4-channel ADC (LTC2174).
3. The ALTERA FPGA generates a correlation matrix of signal powers.
4. To calculate the weighting coefficients, the FPGA can use one of the adaptive algorithms for digital beamforming with maximising the signal-to-(interference-plus-noise) ratio – SINR (Signal-to-Interference-plus-Noise Ratio). This version of the algorithm is suitable for navigation systems, as it takes into account both noise and interference, which ensures reliable signal reception in conditions of intense interference.
5. Application of calculated weighting coefficients in FPGA to process an array of signals from the antenna array outputs to generate an output signal with an improved signal-to-noise ratio.
6. Continuous interference suppression is achieved by spatial filtering in the FPGA to create «zeros» in the directions of the interferers with dynamic adjustment of the weighting coefficients.

CONCLUSIONS

In the course of the study of the «Cometa-M» device, the components of which it consists were identified, their characteristics and interrelationships were investigated, a structural diagram and a simplified description of the algorithms that are most likely to be used in the operation of this device were created. The frequency characteristics of the input stages of this device, which directly form the operating frequency range for further signal processing, were measured.

According to the results of the conducted research, it should be noted the constructive manufacturability of the «Cometa-M» device, namely, with compact dimensions, a rather complex functionality based on the use of DSP is implemented to minimise the impact of interference. The wide capabilities of the ALTERA FPGA used in this device allow implementing signal processing algorithms based on the calculation of the correlation matrix of signal powers from each receiving channel, the calculation of weighting coefficients and their consideration in the formation of «zeros» in the directions of interference signals.

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КОНСТРУКТИВНІ ТА ФУНКЦІОНАЛЬНІ ОСОБЛИВОСТІ МАЛОГАБАРИТНОЇ АНТЕННОЇ РЕШІТКИ «КОМЕТА-М»

У статті представлені результати проведених досліджень конструктивних та функціональних особливостей антенної решітки «Комета-М». Об'єктом досліджень є малогабаритна адаптивна антенна решітка із вбудованим супутниковим навігаційним приймачем, яка активно застосовується ворогом проти України, як основна складова навігаційної системи безпілотних літальних апаратів та інших засобів повітряного нападу. Подібні системи побудовані на базі цифрових антенних решіток та використовуються для підвищення стійкості роботи супутникових навігаційних приймачів в умовах завад, адже призначені для забезпечення просторової фільтрації сигналів від завад.

Досліджено технічні характеристики та особливості функціонування антенної решітки «Комета-М». У ході проведених досліджень визначено структуру побудови, призначення ключових компонентів. Наведено зовнішній вигляд, короткий опис та технічні характеристики основних компонентів. За відсутності можливості однозначної ідентифікації компонентів, виміряні їх технічні характеристики. Це особливо актуально для високочастотних фільтрів, які задають робочий діапазон частот, оскільки діапазон частот, який обробляє антенна решітка, визначає навігаційні системи, сигнали з яких вона може обробити.

За результатами проведених досліджень складена структурна схема та описано принципи роботи «Комета-М», наведено послідовність обробки радіосигналу. Характеристики ключових компонентів, таких як АЦП, ПЛІС та ЦАП, визначають спроможності цієї антенної решітки щодо обробки сигналу, оскільки у даних системах важлива величина розрядності оцифрування сигналів.

Ключові слова: ЦАП, антенна решітка, протидія завадам, діаграма спрямованості, навігаційна система, CRPA, GNSS, «Комета-М», Бп.ЛА.

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EVALUATION OF AIR SHOCK WAVE PARAMETERS AND PROTECTION AGAINST THEM WITH BALLISTIC FOAM CONCRETE

The parameters of the air shock wave during the detonation of a standard charge of TNT with a mass of 1 kg when it falls on barriers made of ballistic foam concrete of four types and the air shock wave flow around this barrier were studied. The thickness of the ballistic foam concrete samples is 300 mm, the density is 600 kg/m³. Empirical formulas of M.A. Sadovsky were used for the calculations. A satisfactory match of the experimental data with the parameters calculated according to the formulas of M.A. Sadovsky was established. In the experiments, it was shown that the amplitude of air shock wave behind the barrier made of ballistic foam concrete decreases by an average of 8–30 times. Approximate estimates based on the research data of other authors (Belinsky I.V., Khristoforov B.D.) predict a reduction of the compression wave that propagates through ballistic foam concrete by no more than 5–10 times. As a result of experimental researches, it was found that the shock waves from the explosions turned the relatively insignificant upper layer of the foam concrete slabs, which is the «sacrificial» layer, into a compressed powder due to the destruction of the inter-pore partitions. In the plane of the surface of the foam concrete slabs, the «sacrificial» layer was described by an

imaginary circle, which is the projection of the explosion. The size of the «sacrificial» layer of ballistic foam concrete destroyed by air shock wave from the frontal side does not exceed 20–40 mm. Spalling phenomena from the back side of the ballistic foam concrete samples were not observed when the air shock wave fell with amplitude of 0.4–0.6 MPa. There are 2 types of ballistic foam concrete with the most effective damping of the compression wave in it. It was established that the most effective in terms of protecting critical infrastructure facilities from the action of air shock waves are foam concrete models of protective structures, which are reinforced with fiber of composition «A» and «B» with a reinforcing layer of composite material applied. It was determined that in these models the deepest zones of destruction of ballistic foam concrete were observed on the front side of the protective structure.

Keywords: charge, air shock wave, protective structures, ballistic foam concrete, critical infrastructure, «sacrificial» layer.

INTRODUCTION

The task of assessing the main parameters of air shock waves: excess pressure at the air shock waves front, impulse and duration of action in the compression phase has always been relevant in the design of explosive works [1–4]. It acquires particular importance in wartime conditions for assessing the impact of various means of destruction on the environment. In addition, increasing the accuracy and reliability of such assessments allows designing effective structures for protecting important infrastructure facilities and new materials for their construction. The availability of data on the parameters of air shock waves, acoustic waves and seismic waves allows us to accurately determine the type of ammunition that hit a particular object in the event of a ground or surface explosion. The main means of destroying civilian objects outside the front-line areas are unmanned aerial vehicles with an explosive mass of $\approx(20\text{--}40)$ kg TNT and cruise and ballistic missiles with an explosive mass in the warhead of $\approx(200\text{--}400)$ kg.

The purpose of the article is to analyze empirical formulas for calculating the parameters of the air shock waves during air, ground and surface explosions of charges of different masses; experimental assessment of their reliability; assessment of dynamic strength, destruction of samples of new building materials – ballistic foam concrete under the action of air shock wave of low and medium intensity.

MATERIALS AND METHODS OF RESEARCH

The research was conducted at a military training ground on a specially created experimental stand. Fig. 1 shows a photograph of a model of a ballistic foam concrete protective structure and a diagram of the location of the experimental stand, test specimens, detonation points and measuring equipment.

The stand for installing the test specimens is a prefabricated reinforced concrete structure (Fig. 1a), which is constructed from two reinforced concrete slabs with dimensions in plan of 2000 x 2000 mm, 300 mm thick, made of concrete of class C16/20, installed vertically at an angle of 90° to each other, on four foundation blocks measuring

1000 x 1000 x 1200 mm, reinforced with a supporting metal frame.

The ballistic foam concrete protective structure samples consisted of the following elements:

- a slab of monolithic ballistic foam concrete, aged for 23 days;
- a slab of monolithic ballistic foam concrete, aged for 23 days with a reinforcing layer of composite material applied.

The number of samples and the parameters of monolithic ballistic foam concrete slabs were determined by the tasks set in the experimental tests. The following parameters were established:

sample No. 1: the ballistic foam concrete slab with a density of 600 kg/m³, dimensions in plan 2000 x 1000 mm, thickness 300 mm;

sample No. 2: the ballistic foam concrete slab with a density of 600 kg/m³, dimensions in plan 2000 x 1000 mm, thickness 300 mm, with a reinforcing layer of composite material applied;

sample No. 3: the ballistic foam concrete slab with a density of 600 kg/m³, dimensions in plan 2000 x 1000 mm, thickness 300 mm, reinforced with fiber of composition «A», with a reinforcing layer of composite material applied;

sample No. 4: the ballistic foam concrete slab with a density of 600 kg/m³, dimensions in plan 2000 x 1000 mm, thickness 300 mm, reinforced with fiber of composition «B», with an applied reinforcing layer of composite material.

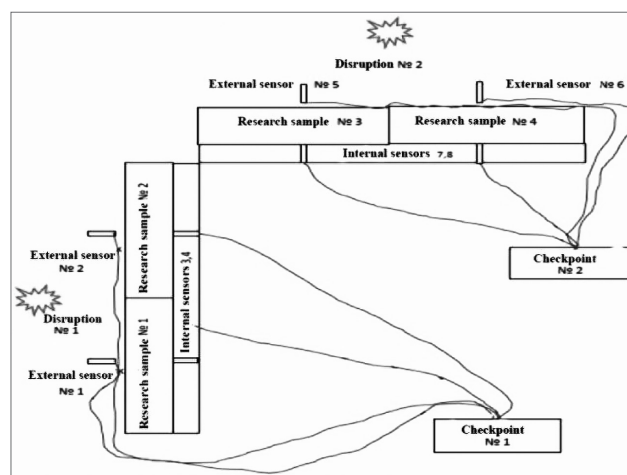
In front of the ballistic foam concrete protective structure model, a wooden mast was installed at a distance of 1.4–1.5 m from the model, where a 1 kg TNT charge was fixed at a height of 1 m from the ground level (Fig. 2a). Each slab on the inside of the angle they form has two niches, which are located at a distance of 1000 mm from the lower edge of the slabs and at a distance of 500 mm from the side edges of the slabs, with a distance of 1000 mm between them. The niches are intended for installing dynamic pressure sensors and laying plastic tubes for passing cables leading to them (Fig. 2b).

The sensors were located near the front surface of the test specimens, as shown in Fig. 2a, as well as the front surface of the reinforced concrete slab or on the back side of the ballistic foam concrete slabs, as shown in Fig. 2b. During the tests, a separate charge was detonated in front of one pair of ballistic foam concrete (samples No. 1 and No. 2) and then in front of the other pair (samples No. 3 and No. 4).

During the tests, the following were measured: dynamic pressure (MPa, at) of air shock waves and dynamic parameters (frequency (kHz), acceleration (m/s²)) of



a)



b)

Fig. 1. Model of a foam concrete protective structure (a) and layout of the elements of the experimental stand (b)



a)



b)

Fig. 2. Model of the ballistic foam concrete protective structure element before the explosion: front view with the placement of the TNT charge and pressure sensors (a) and the location of the sensors on the back side of the concrete slab (b)

vibrations of reinforced concrete slab structures protected by experimental samples of ballistic foam concrete slabs [5–7], when exposed to an air shock wave caused by the detonation of an explosive; the thickness of the «sacrificial» layer of ballistic foam concrete slabs (mm) formed on their surface when damping shock waves.

The following measuring equipment was used to conduct the tests:

- pressure sensors of the PS2300V5 type from the company «Dytran Instruments, Inc.» (USA), which record the maximum pressure from the shock wave on the surface of the ballistic foam concrete slab and on the surface of the reinforced concrete slab (test stand) at the time of the explosion (Fig. 3);
- equipment for transmitting signals from the sensors to a computer and recording them;
- a scale ruler for measuring the thickness of the «sacrificial» layer of ballistic foam concrete slabs.

RESEARCH RESULTS AND DISCUSSION

According to the program and research methodology, methods of mathematical and physical simulation of the interaction of air shock waves with models of the ballistic foam concrete protective structures were applied. As a result, the results of calculations of the main parameters of the air shock waves, the excess pressures that it creates and the loads on the models of foam concrete structures were obtained, as well as the acoustic-dynamic characteristics of the air shock wave and their interaction with the surface of the ballistic foam concrete protective structure and the degree of reduction of the shock pressure on the structures protected by the ballistic foam concrete structure were measured [8–11].

Results of physical modeling (according to Sadovsky M.A.)

For the explosion of charges from a 50/50 TG mixture in air with normal initial conditions, the following formulas were obtained for calculating the main parameters of the air shock wave [12]:

$$\Delta P = 0.85 \frac{C^{1/3}}{R} + 3.0 \frac{C^{2/3}}{R^2} + 8.0 \frac{C}{R^3}, \quad I = 20 \frac{C^{2/3}}{R}, \quad \tau_+ = 1.2 C^{1/6} R^{1/2}, \quad (1)$$

$$0.1 \leq \frac{C^{1/3}}{R} \leq 1.0, \quad (0.1 \frac{\text{kg}}{\text{cm}^2} \leq \Delta P \leq 10 \frac{\text{kg}}{\text{cm}^2}), \quad (2)$$

where ΔP is the excess pressure at the front of the incident shock wave; I is the pressure pulse; τ_+ – the duration of the pressure in the air shock wave in the compression phase.

The law of energy similarity in explosions consists in the fact that the charge as a source of a shock wave is characterized by energy E , which is proportional to the mass of the charge C ($E = CQ$, Q – heat of explosion of 1 kg of explosive). Taking into account chemical losses in explosions in relation to the specific heat of explosion allows us to recalculate the coefficients in these formulas for the case of any explosive. Since TNT was used in the experiments ($Q_1 = 4185$ kJ/kg, $C_1 = 1$ kg), and in the experiments [12] – TG 50/50 ($Q_2 = 4856$ kJ/kg), the condition of energy similarity will be the ratio $E_{TNT} = E_1 = C_1 Q_1 = E_{TG} = E_2 = C_2 Q_2$. Whence $C_2 = 0.862$ kg. For $C_1 = 40$ kg $C_2 \approx 34.5$ kg; for $C_1 = 400$ kg $C_2 \approx 344.7$ kg.

Calculation according to formula (1) for the value of excess pressure on the air shock wave front for TNT charges weighing 1 kg, 40 kg, 400 kg (TG 50/50 – 0.862 kg, 34.5 kg and 344.7 kg) is given in Table 1. The notation in Table 1: ΔP – value of excess pressure on the air shock wave front; R_0 – radius of the charge; R – distance from the center of the charge in m for a charge weighing 1 kg of TNT (column No. 3), 40 kg (column 4); 400 kg (column No. 5); duration of pressure for a charge weighing 1 kg of TNT (column 6); 40 kg (column 7).

The pressure created by the air shock wave on the obstacle is always greater at the front of this wave if the angle of approach of the air shock wave to the obstacle is different from zero [12, 13].

When the air shock wave falls on a hard surface, the excess pressure in the reflected wave usually increases. In the plane wave approximation, the excess pressure in the reflected wave P_2 during direct reflection is determined by the formula [13]:

$$P_2 = P_1 + \frac{2kP_1(P_1 - P_0)}{(k-1)P_1 + (k+1)P_0}, \quad (3)$$

where P_1 is the pressure at the front of the incident air shock wave; P_2 is the pressure at the front of the reflected air shock wave; P_0 is the initial pressure in the air; k is the adiabatic

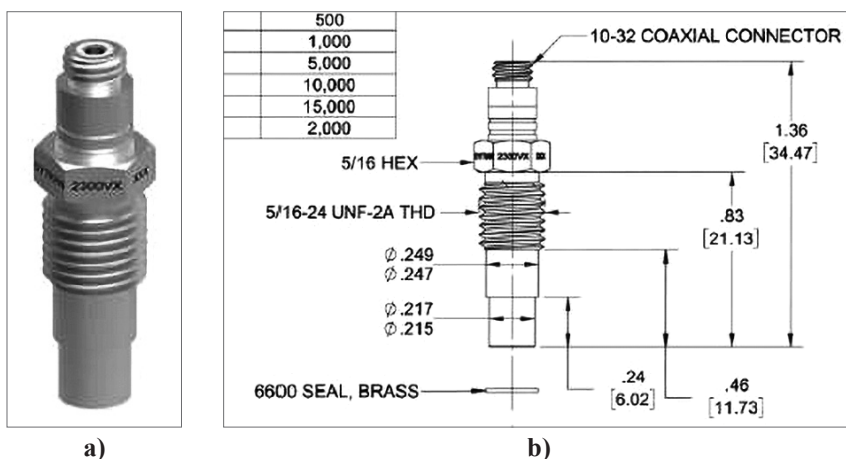


Fig. 3. Dynamic pressure sensor type PS2300V5: photograph (a) and diagram (b)

Table 1. The magnitude of the excess pressure at the air shock wave front and the corresponding distances in m for charges of 1 kg, 40 kg and 400 kg

$p_1 = \Delta p \cdot 10^{-5}, \text{ Pa}$	R / R_0	$R, \text{ m}$	$R, \text{ m}$	$R, \text{ m}$	$\tau_+, \text{ ms}$	$\tau_+, \text{ ms}$
1	2	3	4	5	6	7
10,22	20	1	3,4	7,36	1,17	
8,15	22	1,1	3,74	8,10	1,23	
6,34	24	1,2	4,08	8,83	1,28	
5,42	26	1,3	4,42	9,57	1,34	
4,58	28	1,4	4,76	10,30	1,39	
3,80	30	1,5	5,10	11,04	1,43	4,88
3,35	31,5	1,58	5,36	11,59	1,47	
2,94	33,4	1,67	5,65	12,25	1,51	

index of the air ($k = 1.4$ for an ideal gas). For a strong air shock wave ($P_1 \gg P_0$), formula (3) gives $P_2 = 8P_1$. For $P_1 = 0.458 \text{ MPa}$ at $R \approx 28R_0$ (Table 1), $P_2 = 1.56 \text{ MPa}$.

A distinction is made between regular and irregular (Makhov reflection). Makhov reflection with the formation of a Makhov wave in addition to the incident, reflected waves is realized when $\varphi > \varphi_{pr}$. The fronts of all waves converge to a single point (triple point), which moves at an angle to the reflection surface in a self-similar mode.

If the angle of incidence of the air shock wave on the obstacle is taken into account, the formula for the excess pressure in the reflected wave with regular reflection is a different approach [13]:

$$\frac{P_1}{P_0} = \frac{7}{6} M^2 \sin^2 \varphi_0 - \frac{1}{6} = \frac{7M_0^2 - 1}{6}; \quad (4)$$

$$\frac{P_2}{P_1} = \frac{7}{6} M_1^2 \sin^2 \varphi_1 - \frac{1}{6}; \quad (5)$$

$$\varphi_2 = \varphi_1 - \theta. \quad (6)$$

where $M_0 = D_1/C_0$ – Mach number of the incident wave; $M = M_0/\sin \varphi_0$ – Mach number in the gas when passing through the seal jump; C_0 – velocity of sound in the gas at rest; φ_0 – angle of inclination of the seal jump relative to the reflection surface; M_1 – Mach number of the gas flow in the reflected wave; ϑ – angle of rotation of the gas flow through the incident air shock wave; φ_1, φ_2 – angles of inclination of the direct and reflected air shock wave.

Calculations using formulas (4–6) and others not given in this section for determining the parameters $M_1, \vartheta, \varphi_1, \varphi_2$ are quite complex and can be used to solve specific problems of the interaction of the air shock wave with elements of structures and buildings. If the element of the structure or building is located at a large distance from the charge, then the curvature of the air shock wave front can be neglected and formulas (1–3) can be used to estimate the excess pressure and other parameters of the air shock wave action on

the obstacle. When flowing around ($\varphi_0 = 90^\circ$) $M = M_0$ the pressure does not change.

When detonating a charge on a hard surface, when an air shock wave is formed in a half-space, it is necessary to substitute a doubled charge mass into the formulas. If the barrier is deformed and compressed, then part of the energy goes to its destruction and the formation of an air shock wave in it. Therefore, in the formulas for the air shock wave parameters, it is necessary to substitute the equivalent charge mass, which is equal to $2\eta C$, where the coefficient η takes into account the fraction of the explosion energy that is released into the air. For an absolutely hard barrier, $\eta = 1$. The value of the coefficient η for some barrier materials according to the data of work [13] is given in Table 2.

Near the explosive charge, the law of attenuation of the air shock wave will be different from that shown by formula (1) [1]. At large distances from the charge, the propagation of the air shock wave passes into the acoustic stage. Some data for concentrated charges with spherical symmetry can be found in [12, 13]. For cylindrical charges, see [14].

Irregular reflection occurs only if the reflection angle exceeds approximately 40° and depends on the magnitude of the excess pressure in the incident air shock wave. From the point of view of the action of the air shock wave from an explosion in the air on structures, the greatest interest is the pressure ratio P_1/P_2 . This value changes with the change in the angle of incidence of the wave from $\varphi_0 = 0^\circ$ to $\varphi_0 = 90^\circ$ at a given intensity of the incident wave with the Mach number $M_0 = \text{const}$ (or $P_1/P_0 = \text{const}$). As already noted, with direct reflection P_2/P_1 is calculated by formula (3). With an increase in φ_0 , the ratio P_2/P_1 first decreases, and then with the approach of φ_0 to φ_{pr} it becomes equal, and for weak shock waves it is somewhat larger than with direct reflection. When switching to Mach reflection, P_2/P_1 drops abruptly to a certain value and then smoothly decreases to $P_2/P_1 = 1$ at $\varphi_0 = 90^\circ$. A jump-like drop in P_2/P_1 is observed with strong shock waves with $P_0/P_1 \leq 0.5$. For weak air shock waves, when transitioning to Mach reflection, there

Table 2. Values of the coefficient η for some barrier materials when detonating a charge on a hard surface

Type of obstacle	Steel plate	Reinforced concrete slab	Concrete, rocky soil	Dense loams, clays	Medium density soils	Water
η	1	0,95 – 1	0,85 – 0,9	0,7 – 0,8	0,6 – 0,65	0,55 – 0,6

is a slight smooth increase and then a sharp decrease in P_2 / P_1 . In fact, formula (3) is universal for estimating the excess pressure «from above» on structures during air shock wave reflection.

RESULTS OF PHYSICAL SIMULATION

The results of physical simulation on an experimental stand using visual studies using a high-speed video camera and instrumental measurements of acoustic pressure on the surface of a ballistic foam concrete protective structure, as well as on the surface of a concrete structure protected by a layer of ballistic foam concrete, showed the following. As a result of video shooting, about 2 thousand video frames were obtained, which allowed us to determine in detail the features of the explosion formation from the process of its formation to degeneration. The features of the formation of an air shock wave, its time of existence and interaction with protective structures were determined.

Instrumental measurements of dynamic pressure from an air shock wave on the surfaces of the ballistic foam concrete test specimens No. 1 and No. 2 from their front and back sides are shown in Fig. 4a.

The measurement results show that the air shock wave pressure on the front surfaces of the ballistic foam concrete protective structure of models No. 1 and No. 2 is significantly higher (red and blue curves in Fig. 4) than on the back surface of the ballistic foam concrete or on the surface of the protected concrete wall model (green and purple curves). This confirms that the ballistic foam concrete protective layer of models No. 1 and No. 2 significantly reduces the air shock wave pressure generated by the detonation of a 1 kg TNT charge at a distance of 1.4–1.5 m from the ballistic foam concrete structure model, on the protected concrete wall by up to 10 times.

The results of measuring the dynamic pressure from the air shock wave generated by the detonation of a 1 kg TNT charge at a distance of 1.4–1.5 m from the model of the ballistic foam concrete structure, on the surfaces of the

experimental ballistic foam concrete samples No. 3 and No. 4 from its front and back sides are shown in Fig. 4b.

As in the case of ballistic foam concrete protective structures models No. 1 and No. 2, significant decreases in the pressure of air shock waves on the ballistic foam concrete surface of models No. 3 and No. 4 on their front and rear surfaces were observed, see Fig. 5. At the same time, the pressure of the air shock wave was almost the same as in the conditions of explosion No. 1 (near ballistic foam concrete structure models No. 1 and No. 2), but the dynamic pressure on the rear part of the ballistic foam concrete structure or on the surface of the protected concrete wall became significantly lower. This corresponds to the results of comparing the indicators of dynamic pressure sensors on the front surface of the ballistic foam concrete structure (red and blue curves in Fig. 4b) and on the rear surface of the ballistic foam concrete protective structure (green and brown curves). The measurement results show that these ballistic foam concrete structure models dampen the air shock wave even more and the damping coefficient reaches several tens of times.

Comparing the results of calculations using formula (1) (Table 1) with experimental data, we can conclude that there is a satisfactory agreement in terms of the amplitude of the air shock wave and a much worse agreement in terms of the pulse duration (Table 1, Table 3). This difference can be explained by different atmospheric conditions: in our experiments the weather was rainy and the air humidity was (90–100) %. This increases the air density. In experiments [12] the humidity could be different. In addition, there were several reflection surfaces in the experimental conditions: sample No. 1 and No. 2, sample No. 3 and No. 4, soil, etc. (Fig. 1, Fig. 2). The reflection surface itself is not absolutely rigid, as for formula (3). It deforms and collapses during the reflection process. Additional pressure peaks that appeared after a certain period of time are associated with the reflection of air shock wave from the soil base and from the surrounding soil embankment (Fig. 4).

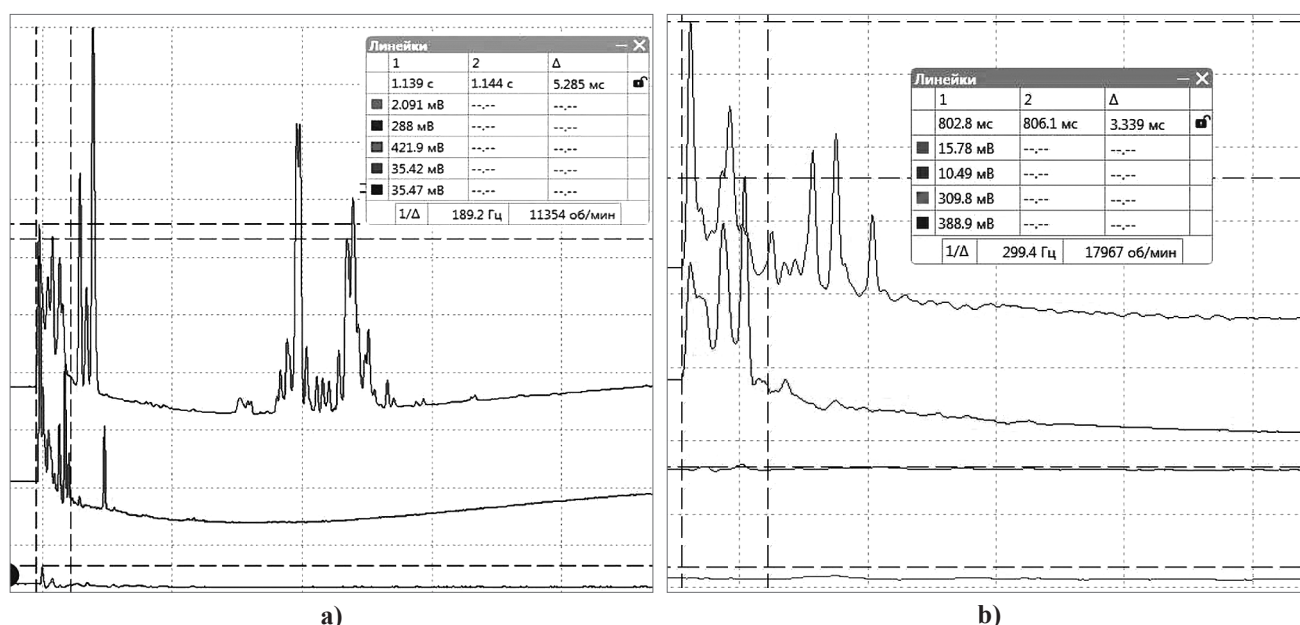


Fig. 4. Shapes of pressure pulses on the surfaces of experimental samples of the ballistic foam concrete protective structures models No. 1 and No. 2 (a) and No. 3 and No. 4 (b)

Table 3. Parameters of dynamic pressure measurements during the fall and reflection of shock waves

Object / structure	Measuring instruments	Sensor readings, mV	Duration of pulsed pressure fluctuations, ms	Dynamic pressure*, at	Dynamic pressure drop (times)
Explosion No 1					
Experimental sample No. 1	External sensor No. 1	288	5,285	19,2	8,1
	Internal sensor No. 3	35,42	5,285	2,36	
Experimental sample No. 2	External sensor No. 2	421,9	5,285	28,12	11,9
	Internal sensor No. 4	35,47	5,285	2,37	
Explosion No 2					
Experimental sample No. 3	External sensor No. 5	388,9	3,339	25,93	24,7
	Internal sensor No. 7	15,78	3,339	1,05	
Experimental sample No. 4	External sensor No. 6	309,8	3,339	20,65	29,5
	Internal sensor No. 8	10,49	3,339	0,70	

Notes: * – dynamic pressure was calculated based on sensor calibration, 15 mV corresponds to 1 at.

After the blasting work, photo-fixation and measurement of the effects of air shock waves on the surface of the ballistic foam concrete protective structures samples were carried out. The results of the study showed that the shock waves from the explosions turned the relatively insignificant upper layer of the ballistic foam concrete slabs, which is the «sacrificial» layer, into compressed powder due to the destruction of interpore partitions. In the plane of the surface of the ballistic foam concrete slabs, the «sacrificial» layer was described by an imaginary circle, which is the projection of the explosion, with a diameter of about 1 m.

The thickness of the «sacrificial» layer decreased from the center of the circle to the periphery, and in the center of the circle was:

- (12–16) mm in test sample No. 1;
- (12–16) mm in test sample No. 2;
- (18–22) mm in test sample No. 3;
- (36–38) mm in test sample No. 4.

Fig. 5 presents photographs of the tested prototypes with the minimum and maximum thickness of the «sacrificial» layer.

Practical and scientific interests are the state of the entire ballistic foam concrete sample as a result of weakening the material throughout its depth by a direct wave of loading and unloading waves. For this purpose, methods of ultrasonic diagnostics of materials are used. A decrease in the velocity of ultrasound in the material indicates the appearance of new microcracks and cavities, which indicates a weakening of the strength properties of the material.

Researches of the attenuation of air shock wave in porous media were carried out quite widely, starting from the 60–70 s of the last century. These researches were carried out mainly with the aim of studying the effect of underground and surface nuclear explosions on underground structures and to study the dynamic properties of rocks and obtain shock adiabats [15, 16]. In particular, in [15] it is shown that the energy of the air shock waves E_{ASW} in a camouflage explosion in porous salt (NaCl) with a porosity of 2 %, 13.5 % and 20 % at relative distances from the charge $R / R_0 = (1-5)$ decreases in relation to the total energy E_0 of the explosion by approximately 0.7 to 0.1 and less for highly porous salt (20 %). The patterns



a)

b)

Fig. 5. «Sacrificial» layer of the ballistic foam concrete slabs after explosions: test sample No. 1, with minimum layer thickness (a), test sample No. 4, with maximum layer thickness (b)

of attenuation of flat air shock wave in salt samples of different porosity as a result of impact with a flat aluminum impactor with an impact velocity of 1.7 km/s are also close to these patterns. The difference is only in the shape of the attenuation curves, which is explained by the geometry of the air shock wave front. According to these experimental data, at relatively large distances $\approx (10-100)\Delta$ (Δ is the thickness of the impactor, in our case, approximately the width of the air shock wave in the compression phase) the air shock wave attenuates 5–10 times depending on the porosity (2 %–20 %).

CONCLUSIONS

1. The results of the semi-real-life experiment showed that the parameters of the air shock wave from the explosion of a reference TNT charge weighing 1 kg (pressure in the reflected air wave) are in relatively satisfactory agreement with the data of calculations with empirical formulas of other authors.

2. It was determined that the dynamic pressure of the air shock wave on samples of ballistic foam concrete decreases on average by 8–30 times.

3. It was established that the dynamic shock pressure in the compression wave propagating through ballistic foam concrete, according to other authors, decreases by no more than 5–10 times.

4. It was shown that the thickness of the destruction zone of the ballistic foam concrete on the front side is not more than 20–40 mm. Spalling phenomena on the back side under the action of an air shock wave of low intensity (0.4–0.6) MPa were not observed.

5. It was established that the most effective in terms of protecting critical infrastructure facilities from the effects of air shock waves are the ballistic foam concrete protective structures of models No. 3 and No. 4, which are reinforced with fiber of composition «A» and «B» with an applied reinforcing layer of composite material, but at the same time, the deepest zones of destruction of ballistic foam concrete were observed on these models on the front side of the protective structure.

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ОЦІНКА ПАРАМЕТРІВ ПОВІТРЯНИХ УДАРНИХ ХВИЛЬ ТА ЗАХИСТ ВІД НИХ БАЛІСТИЧНИМ ПІНОБЕТОНОМ

Досліджено параметри повітряної ударної хвилі (ПУХ) при детонації стандартного заряду TNT (тро-тил) масою 1 кг при падінні її на перепони із балістичних пінобетонів чотирьох типів і обтіканні ПУХ цієї перепони. Товщина зразків пінобетону – 300 мм, щільність – 600 кг/м³. Для розрахунків використано емпіричні формули Садовського М.А. Встановлено задовільний збіг експериментальних даних з параметрами, розрахованими за формулами Садовського М.А. В експериментах було показано, що амплітуда ПУХ за перепорою із пінобетону зменшується в середньому у 8–30 разів. Наближені оцінки за даними досліджень інших авторів (Белінский І.В., Христофоров Б.Д.) прогнозують зменшення хвилі стиснення, яка розповсюджується по пінобетону, не більше, ніж в 5–10 разів. В результаті експериментальних досліджень було встановлено, що ударні хвилі від вибухів перетворили відносно незначний верхній шар пінобетонних плит, що є «жертвним» шаром, на спресований порошок, через руйнування міжпорових перегородок. У площині поверхні пінобетонних плит, «жертвний» шар описувався уявним колом, що є проекцією вибуху. Величина «жертвного» шару пінобетону, зруйнованого ПУХ з фронтальної сторони, не перевищує 20–40 мм. Відкольних явищ з тильної сторони на зразках пінобетону при падінні ПУХ амплітудою 0,4–0,6 МПа не спостерігалось. Виділено 2 типи балістичного пінобетону з найбільш ефективним гасінням хвилі стиснення в ньому. Встановлено, що найбільш ефективними з точки зору захисту об'єктів критичної інфраструктури від дії повітряних ударних хвиль є пінобетонні моделі захисної споруди, які армовані фіброю складу «А» та «Б» з нанесеним посилюючим шаром композитного матеріалу. Визначено, що при цьому на цих моделях спостерігалися найглибші зони деструкції балістичного пінобетону з фронтальної сторони захисної споруди.

Ключові слова: заряд, повітряна ударна хвиля, захисні споруди, пінобетон, критична інфраструктура, «жертвний» шар.

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CONCEPTUAL FOUNDATIONS FOR BUILDING A SYSTEM FOR COMPREHENSIVE PROTECTION OF CRITICAL INFRASTRUCTURE FACILITIES FROM AIR TREATS

The main actions of the enemy deep in the country are aimed at destroying critical infrastructure facilities. Effective protection of important facilities requires a comprehensive approach and officials must understand the possible ways and methods of averting air threats to ensure the survivability of protected facilities. The system of comprehensive protection of a critical infrastructure facility is designed to implement a set of measures to reduce the likelihood of damage to the facility as a result of air attack strikes. The article presents the results of the analysis of the main characteristics of air attack weapons, in particular the range and mass of the warhead. The conducted set of studies showed low values of the effective scattering surface of strike weapons in the radar range. The results of modeling detection capabilities, including low-altitude movement routes, are presented. For operation in the interests of direct detection of air targets and target designation for mobile fire groups, a comparative analysis of the capabilities of small-sized radars was conducted. A list of radio reconnaissance means for detecting air targets and target designation for electronic warfare means is proposed. A list of means of radio jamming is proposed as part of the functional countermeasure subsystem. Means of distorting the radar and optical portrait, as well as means of masking objects of protection, are considered. Variants of equipping the fire damage subsystem are presented. To increase the detection range of low-altitude air targets, it is proposed to install radar means on air balloon platforms. The balloon equipment subsystem can also be used to install optoelectronic and acoustic detection means, means of radio reconnaissance and electronic warfare. According to the results of the study, the composition of the system of complex protection of critical infrastructure objects from strikes by enemy air attack means is proposed.

Keywords: *critical infrastructure facility, protection system, air attack means, detection, camouflage, counteraction to air threats.*

INTRODUCTION

During the fighting, the enemy changed the nature of the armed struggle. Currently, the main efforts are focused on the destruction of critical infrastructure facilities of Ukraine (bridges, transport hubs, important industrial enterprises and other important state facilities).

Approaches to ensuring the protection of critical infrastructure (CI) facilities consist of implementing a set of measures to prepare a regulatory framework [1–3], formalizing the characteristics of air attack means [4], forming a threat model [5], studying the revealing characteristics of the facility and the enemy's intelligence capabilities, preparing proposals for improving the protection of the facility [6], substantiating the rational scope of measures and means of protection [7] and ways of practical implementation of protection measures taking into account existing experience and methodological recommendations [8]. The enemy developed the corresponding methodological approaches in the scientific community in advance [9]. Despite the sufficient elaboration, in particular, of the regulatory framework for ensuring the protection of critical infrastructure facilities, the experience of deterring aggression from the first days showed a sufficient level of competence of responsible officials only in the field of control and distribution of financial resources. Responsibility for implementing practical measures to protect facilities was promptly transferred to other military and paramilitary structures. At the same time, effective protection of important facilities requires a comprehensive approach and officials must understand possible ways and methods of averting air threats to ensure the survivability of protected facilities.

The OKI complex defense system is designed to implement a set of measures to reduce the probability of damage to an object due to strikes by enemy air attack vehicles (AAVs), namely cruise missiles and loitering munitions (kamikaze UAVs). Thus, a pressing problem arises in developing methodological approaches to organizing a complex of organizational and technical measures aimed at protecting Ukraine's critical infrastructure from enemy air defenses in conditions of limited resources.

The purpose of the article was to analyze the characteristics of the enemy's strike AAVs, world experience in detecting and countering AAVs, as well as develop methodological approaches to building a system of comprehensive protection of critical infrastructure facilities.

RESEARCH RESULTS

Characteristics of AAVs

For long-range damage, the enemy most widely uses the following air attack vehicles:

- land-, sea- and air-launched cruise missiles of the type 9M727/728/729 (Iskander complex), Kh-101, Kh-59, Kh-69, Kh-22/32, Kh-35, 3M14 «Caliber», 3M22 «Zircon», 3M55 «Onyx»;
- ballistic and aeroballistic missiles of ground and air complexes of the type 9M723 (Iskander complex), type 9-S-7760 (Kinzhal complex);
- loitering munitions (kamikaze UAVs) like the Shahed-131 («Geranium-1») or Shahed-136 («Geranium-2») type.

Closer to the contact line, they are actively used:

- FAB equipped with universal planning and correction modules;
- unified inter-service planning ammunition;
- anti-aircraft guided missiles 5V55 from the S-300 air defense system (various modifications) and 48N6 from the S-400 air defense system (various modifications).

Strike weapons carriers launch them, usually outside the air defense system of the Armed Forces of Ukraine (Fig. 1).

The existing armament and military equipment of the air (missile) defense of the Armed Forces of Ukraine are focused on performing combat missions directly on the line of contact with the enemy (Donetsk, Kherson, Kharkiv directions) and on covering the main administrative and industrial centers of Ukraine (Kyiv, Dnipro, Odesa, Kharkiv, Mykolaiv, etc.) from air strikes. The length of the borders with the enemy is about 2400 km, which determines the unhindered passage of the ZPN into the territory of Ukraine. The list of critical infrastructure facilities of Ukraine is very large, characterized by hundreds of names. Therefore,

covering all critical infrastructure facilities of Ukraine from strikes by existing forces and means is currently complicated.

From the point of view of the ability to detect enemy SPMs by national radar means, they are characterized by indicators of radar visibility, the study of which is carried out by specialists of the Central Scientific Research Institute of Armament and Military Equipment of Armed Forces of Ukraine based on the results of software modeling on the software and hardware complex for modeling electromagnetic aspects of the functioning of AMEs Ansys Academic Research HF. The conducted set of studies showed (Table 1) that enemy SPMs are characterized by a low value of the effective scattering surface in the radar range.

It should be noted that the application of promising methods for detecting AAVs using multi-position passive (semi-active) radars requires improving the methods for studying the characteristics of radar visibility and expanding the characteristics to bistatic or multistatic backscatter diagrams. The effectiveness of the use of each AAVs is

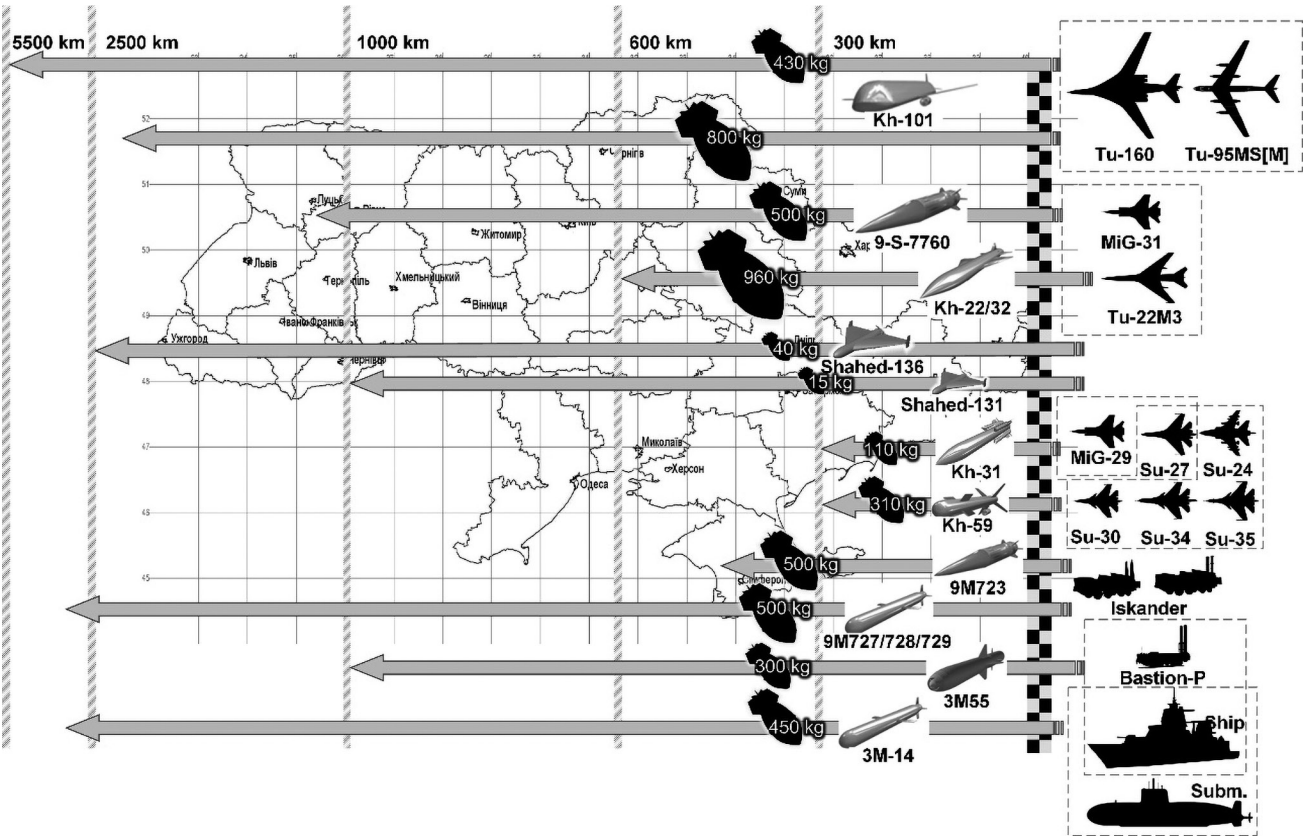


Fig. 1. Results of the analysis of AAVs capabilities

Table 1. Median RCS value [m²] of typical enemy AAVs (f=10 GHz)

Sample	9-S-7760	Kh-101	Kh-55	Kh-22/32	Kh-59	R-37	3M-55	3M-14	UMPK				UPAB-1500B	GROM-1E/2E	UMPB	Shahed-136
									FAB-250	FAB-500	FAB-1500	FAB-3000				
RCS	0,6	0,8	1,7	1,5	0,3	0,8	0,8	0,5	0,1	0,2	0,4	0,8	0,9	0,1	0,1	0,1

determined by a set of sensors from the control system, as well as additional means that help counteract its destruction or disruption of the trajectory of movement and the defeat of the intended target.

Developing the most rational ways to counter enemy AAVs requires improving the air strike threat model by taking into account typical trajectory data, dynamic characteristics of AAVs, target characteristics of heterogeneous sensors from the AAVs, as well as by assessing the main consequences of the regular operation of the AAVs warhead at different indicators of target defeat accuracy.

AAVs detection subsystem

Radar detection. Radar devices are designed for early detection of FPV approaching the protected object, determination of their movement parameters, transmission of received data about FPV to the control and information interaction subsystem.

Low RCS values lead to a decrease in the potential for detecting AAVs by radar stations (Fig. 2).

In addition, the deterioration of the radar detection range of the Cruise missile (CM) is due to the low flight altitude of the missiles (Fig. 3).

Therefore, to improve the potential radar detection range, one can consider installing the radar on high-altitude objects (for example, towers) or on air carriers such as balloons.

The main requirements for radar detection means of AAVs as part of the KI protection system are to ensure high mobility, autonomy of operation and short time for transfer to a combat (transport) position. The low-altitude nature of the AAVs flight may require the installation of a radar transceiver unit at a height (on a mast, tactical tower or structural elements of structures) to ensure the required detection range or placement on a mobile base to quickly increase detection capabilities in the most threatening directions, based on the

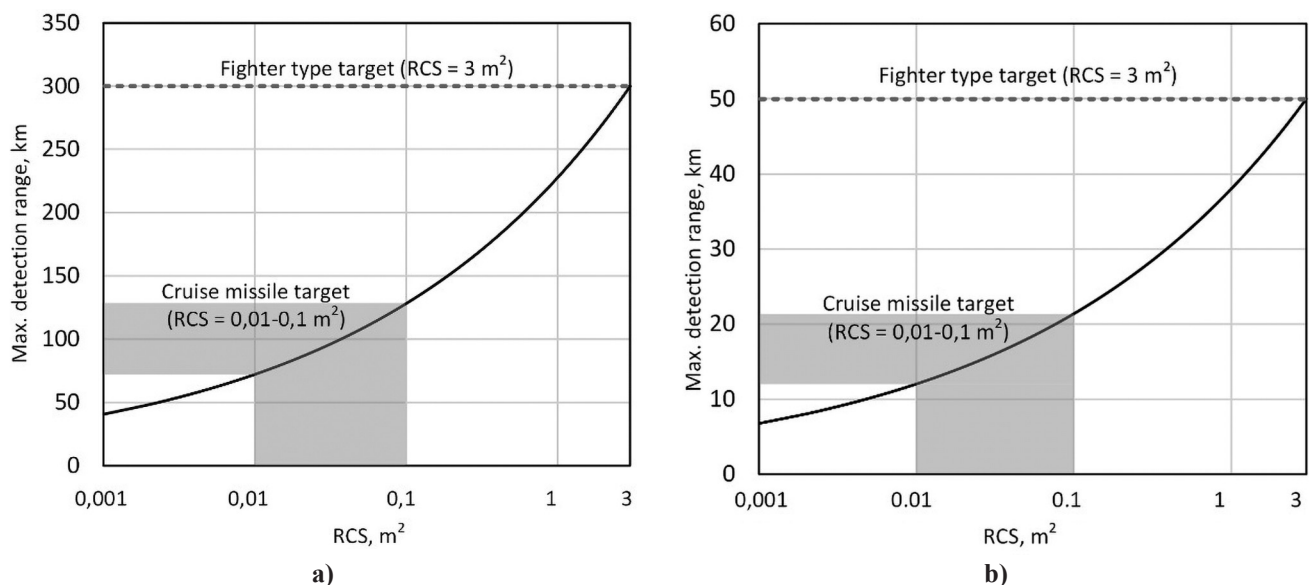


Fig. 2. Results of the assessment of the potential detection range of Cruise missile-type targets compared to a fighter-type target by the long-range (a), as well as medium and short-range (b) anti-aircraft missile system surveillance radar, calculated using the basic radar equation

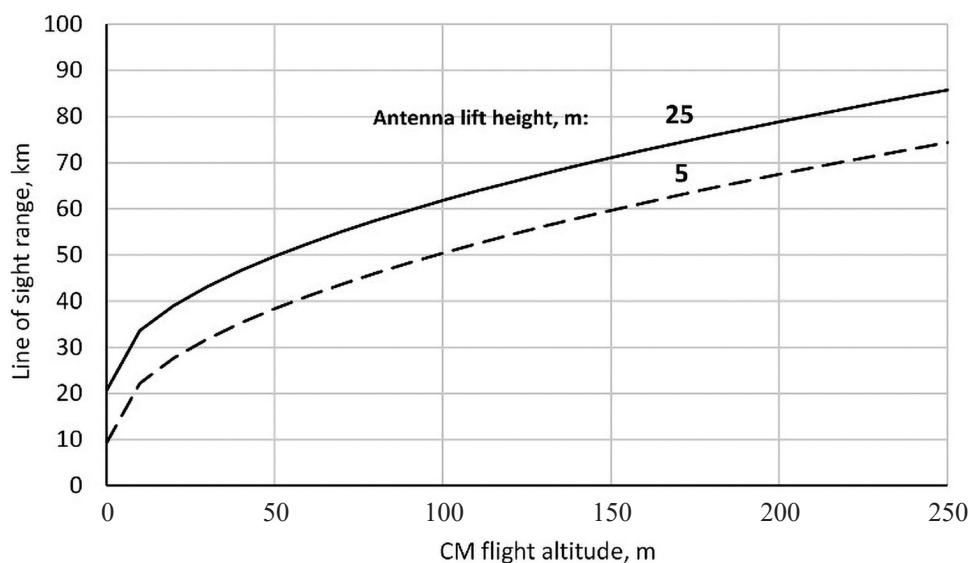


Fig. 3. Results of evaluating the direct visibility range of the radar during flight for different antenna elevation heights

air situation. To simplify installation and maintenance, AAVs detection radars should, if possible, be non-rotating. Such requirements are best met by using modern technologies for constructing solid-state phased (digital) antenna arrays. Possible variants of radars [10] are given in Table 2.

It should be noted that the experience of repelling armed aggression has shown the appointment of radar facilities as priority targets. This requires the development of passive (semi-active) detection means. The current state of development of the theory of construction of passive (semi-active) radar facilities requires the improvement of the scientific and methodological apparatus substantiation of the tactical and technical characteristics of the relevant means of detecting AAVs.

Detection by additional means. Additional means of detecting AAVs:

- optoelectronic means;
- ER-means;
- acoustic means;
- means for detecting launches (including space-based) and monitoring the flight of the CM from partner countries.

The experience of using optoelectronic means of detecting air targets has shown the need to improve optical detection methods in the direction of increasing the speed of space inspection and increasing optical sensitivity.

Increasing the effectiveness of the use of radio reconnaissance means is advisable to be carried out on the basis of the use of a priori data of the threat model. RF-means provide additional target designation to both detection means and electronic warfare means.

It is advisable to choose ER-means in accordance with the importance of the object or group of objects and taking into account the possible integration of data of the radio-electronic environment. Possible options for radio-technical reconnaissance means [11] are given in Table 3. It should be noted that some of the above samples belong purely to military equipment and can be functionally involved in the performance of tasks of protection of the KI.

Joint use of radar, optical, radio and acoustic means of detecting AAVs requires correct integration of coordinate data on the air situation. To perform the tasks of classifying targets and developing recommendations on rational countermeasure options, it is advisable to use elements of artificial intelligence. Thus, for early detection of CM when approaching critical infrastructure facilities of Ukraine, it is advisable to use:

- domestic and foreign means of radar and optical detection of CM;
- foreign means of radar and optical detection of CM based on space (military and technical assistance of partner countries);

Table 2. Variants of small-sized radars for equipping anti-aircraft defense units of the KI

Name	Country of origin	Freq. range, GHz	Azimuth viewing area, degrees	Detection range (RCS 0,01 m ²), km	Coord. recogn. accuracy:		Number of goals that are exceeded	Weight, kg
					distance, m	azimuth, deg.		
ELM-2016NG	Israel	1-2	360 	10	30	0,5	60	b/r
PGSR-3i Beagle	Israel	8-12	6-345 	3	10	0,4	600	b/r
ELM-2026B	Israel	8-12	360 	3,6	30	0,3	100	75
DAiR	Israel	8-12	(1-4)U×110	5	b/r	0,3	10000	1U×27
RPS-42	Israel	2-4	(1-4)U×90	5	b/r	b/r	b/r	1U×30
RPS-82	Israel	2-4	(1-4)U×90	10	b/r	b/r	b/r	1U×58
Spexer 2000	Germany	8-12	(1-3)U×120	4,3	b/r	b/r	b/r	b/r
GO-12	Germany	12-18	360 	4	50	b/r	30	16
ACAR	Turkey	12-18	10-360 	1,9	d/y	b/r	b/r	b/r
FIELDctrl Range	Poland	8-12	(1-4)U×90	5	3	b/r	b/r	b/r
FIELDctrl Follow	Poland	8-12	1U×20	10	1	b/r	b/r	b/r
A422 DRS	Britain	15-17	(1-4)U×90	2,7	60	0,5	b/r	1U×25
PSTAR	USA	1-1,4	360 	b/r	200	2	b/r	b/r
SR Hawk	USA	16,4	360 	4	10	0,2	350	b/r
GA9120	USA	3-3,3	3U×120	2	10	b/r	b/r	1U×41
ARSS	USA	8-12	360 	3	25	b/r	300	19
RDN-170	China	8-12	360	5	10	1	b/r	b/r
Лис-2М	Ukraine	36	360 	1	25	1	b/r	40
112L1 Борсук-А	Україна	36	360 	0,3	25	1,5	b/r	5,5

Note:  – rotational system; b/r – data is being refined.

Table 3. Variants of ER-means for equipping anti-aircraft defense units of the KI

RF-station type	Country	Producer
Wolfpack 210 (WP210), WINGMAN-100	Denmark	MyDefence
Drone Detection System DTS-2458	Estonia	RANTELON OÜ
GES-210	Israel	Elisra Group
AeroScope	China	DJI
AARTOS X9-19 Rack Version Dron Detection System	Germany	Aaronia
RF-360RF	Germany	Dedrone
ARDRONIS-D, PR-100, Argus-M2, DDF119, FSH-20	Germany	Rhode&Schwarz
MUROS-S	Germany	Elettronica Group – ELT GmbH
MSR-W	Poland	PIT
MUR-20	Poland	WZE
Gunica PRP-25M, PRP-25S	Poland	PIT-RADWAR S.A.
TCI 803[S], 903[S]	USA	TCI INTERNATIONAL
AN/PRD-13 (V)3	USA	L-3 Linkabit
KrakenSDR	USA	KrakenRF Inc
DroneFox, Scorpion	USA	WhiteFox Defense Technologies, Inc
Archon-S	Ukraine	Company
RPS-7 «Ingul», Kolchuga-MK	Ukraine	Company
ADMU-12	Ukraine	Company
KVS-UJS, AD-1	Ukraine	Company
FRANEK, TINY SA ULTRA 2.0	Ukraine	Company
TRC 6200-DF	France	Thales Land & Joint System
VERA-E, VERA-NG	Czech	ERA
S RTP	Czech	ERA
Sirius Compact, CRS-8000	Sweden	Saab AB

- domestic and foreign means of acoustic detection of CM (creation of a system of acoustic sensors);
- domestic and foreign means of radio reconnaissance of CM.

In order to detect enemy radars early when approaching critical infrastructure facilities of Ukraine, timely processing of information and issuing information to the control points of the unified state system of physical security of critical infrastructure facilities of Ukraine, it is advisable to consider the option of using domestic and foreign radar detection means of radars on towers and/or balloons, which may be the subject of further research.

Functional countermeasure subsystem.

Electronic warfare means. Reducing the effectiveness of the use of AAVs can be achieved by electronic suppression of radio equipment:

- radio altimeter receiving channels (CM of the type Kh-101, Kh-59, 3M-14);
- receiving antennas of satellite navigation systems (AAVs of all types);
- active seeker (missiles of the type 3M-14, 9M728/729, 3M55, Kh-59, Kh-55, 9-S-7760).

The proposed list of electronic warfare means [12–14] is given in Table 4.

Individual EW means can be considered for installation on an aerostat complex. However, the issue requires additional research. The EW means listed in Table 4 can be

used mainly to counter AAVs. Countering cruise missile-type anti-aircraft missiles currently requires improvement in terms of EW.

Means of distorting the KI radar portrait. Means of distorting the KI radar portrait are designed to create a false situation in terms of radar. The subjects of counteraction are space-based radar means, as well as radar-seeking systems.

The reduction in effectiveness is achieved by misleading the enemy regarding the location of the most important objects (the spatial structure of the KI), as well as by disrupting the acquisition of the radar-homing seeker target (missiles of the type 3M-14, 9M728/729, 3M55, Kh-59, Kh-55, 9-S-7760) by the radar portrait.

It is advisable to install the appropriate means both directly on the KI and near it to deform the general radar portrait of the area. The proposed list of simulators of infrastructure objects in the radar range is given in Table 5–6.

The direction of further scientific research is the substantiation of methods for forming specified levels of radar visibility (both reduction and increase), as well as methods for forming false radar portraits of KI of various composition and size).

Means of distorting the optical portrait of KI (in the visible and infrared range). Means of distorting the optical portrait of OKI are intended for forming a false situation in optical terms in the visible and infrared ranges. The subjects

Table 4. Variants of EW-means for equipping anti-aircraft defense units of the KI

Type of electronic warfare equipment	Country	Producer
DroneSentry, DroneGun Tactical, DroneNode	Australia	DroneShield
J 360 C7/7	Austria	EW Drone Passion GmbH
Sky Net Longbow, Recurve Max, Recurve	Britain	Kirintec Ltd.
L3 Drone Guardian	Britain	L-3 Communications ASA Ltd
SKYPERION	Britain	METIS Aerospace Ltd
Claw C-UAS	Britain	Enterprise Control Systems Ltd.
AUDS	Britain	Blighter Surveillance Systems Ltd.
NIGHTFIGHTER	Britain	Steel-Rock Technologies
Falcon Shield	Britain	Leonardo Airborne and Space Systems
GGJ-100-2-01	Estonia	Rantelon
C-Guard DroneNet	Israel	Netline Communications Technologies
ReDrone	Israel	Elbit Systems
Drone Guard	Israel	Elta Systems Ltd.
Drone Dome	Israel	Rafael Advanced Defense Systems Ltd.
MP807	Israel	Phantom Technologies Ltd.
ADRIAN	Italy	Elettronica Group - ELT Roma
Sky Sweeper	Jordan	Jordan Electronic Logistics Support Co.
Ancile	Canada	Allen-Vanguard
CT-4001PH, PH2	China	R&R Group
ATJ6-120-20	China	Action Technologies Co., Ltd
EDM4S-UA	Lithuania	NT Service
ARDRONIS-R, -P, (-D)	Germany	Rohde & Schwarz
HP-47	Germany	H. P. Marketing & Consulting
XPELLER	Germany	Hensoldt Holding Germany GmbH
Guardion	Germany	Diehl Defence GmbH
HP 47, 3055T, 3962 H	Germany	H.P. Marketing & Consulting Wuest GmbH
MAD-DOS	Poland	MADDOS Sp. zo. o.
ApolloShiel [Portable] C-UAS, RFG Counter-Drone RF Gun	USA, Israel	ApolloShiel
ADEP Blade	USA	Systems & Processes Engineering Corporation
SkyTracker CORIAN / AWAIR / Small Form Factor	USA	CACI International, Inc.
Drone Tracker	USA	Dedrone
ICARUS	USA	Lockheed Martin
Silent Archer	USA	SRC, Inc.
Drone Defender	USA	Battelle
IHTAR, IHAVASAR	Turkey	ASELSAN
Enclave	Ukraine	Company
CEC-N1/N2, Cloud	Ukraine	Company
QUERTUS AD, Vepr, KRAKEN, KSVG-6	Ukraine	Company
Fog, Contour-1/2/3, Nota-SV, Bukovel-AD,-PP, Zahist-ALD, -AL, -AF	Ukraine	Company
AD2, AD2.E	Ukraine	Company
Tornado-4M	Ukraine	Company
Foil	Ukraine	Company
MOROK 3, 4, 5; TOR; MOLOT	Ukraine	Company
HYMO XL, L, M, S	Ukraine	Company
Octave C, Note	Ukraine	Company
Volcano	Ukraine	Company
Galagaz	Ukraine	Company

Table 4. (continued)

Type of electronic warfare equipment	Country	Producer
Ai-Petri SV	Ukraine	Company
Drone Defeater	France	SESP
Counter UAS	France	Thales Air Systems
CerbAir Stationary Unit	France	CerbAir
DRONE SNIPER	France	ITHPP
Airfence 7.0	Finland	Sensofusion
RTX-2000X	Switzerland	Meritis

Table 5. Domestic samples of radar signal reflectors

Imitation tool	Main characteristics				
	Length of the probing signal 6,66 sm			Petal width	
	Maximum RCS values for triangular design (edge length 1 m)	Maximum RCS values for two-sided design (edge length 1 m)	Maximum RCS values for two-sided design (face dimensions 3x6 m ²)	The main one is in a triangular design	Side in double-sided design
Corner reflector «Corner»	8480 m ²	19000 m ²	6000000 m ²	32 deg.	27 deg.

Table 6. Foreign samples of radar signal reflectors

Imitation tool	Main characteristics	
	Maximum RCS values, m ²	Petal width, deg.
Luneberg Lens Reflector (USA)	100	120
	40	100
	4	90
	0,1	90

of counteraction are space-based optical-electronic means, as well as OE-GOS (missiles of the type 9M723, 9-S-7760) and OE-KENS (missiles of the type Kh-101).

It is advisable to install the corresponding means both directly on the KI and near it to deform the general optical portrait of the terrain. The proposed list and tactical and technical characteristics of optical camouflage means are given in Table 7.

The direction of further scientific research is to substantiate methods for sufficient deformation of the optical portrait based on the characteristics of optoelectronic sensors of the AAVs.

Engineering barriers

Engineering barriers are designed to directly stop the approach of the AAVs to the KI structures, as well as to reduce the consequences of the detonation of the AAVs warhead near the KI structures.

Due to the limited quantitative composition of anti-aircraft missile systems, the direction of further research is to

substantiate the possibilities of deploying air-based network barriers based on aerostat systems on the approaches to critical infrastructure facilities.

Fire damage subsystem

If necessary, the KI protection system can be situationally (functionally) involved in the medium and short-range air defense military means. The predominant composition of the fire damage means of the ZPN, which is part of the OKI protection system:

- anti-aircraft small arms (machine guns);
- short-range air defense systems of the ITTEL-1 type (FrankenSAM, USA), «RAVEN» (Great Britain), «Crotale» (France), «Avenger» (USA), SAM «Osa-AKM», SAM «Stormer-HVM», etc.;
- MANPADS of the «Stinger», «Martlet», «Starstreak», «Mistral», «Piorun», «Igla» type;
- anti-aircraft self-propelled artillery installations of the «Gepard 1A2», «Skynex», ZSU 23-4M-A1 (Shilka) type, etc.;

Table 7. Optical masking devices

Type of camouflage kit	Main characteristics				
	Detection range by optical reconnaissance means, m	KIt weight, kg	Total area, m ²	Size of elements, m	Application temperature range
Optical camouflage kit MKO (Ukraine)	500	60	216	3×6	-45 °C + 50 °C
Deforming painting	b/r	b/r	b/r	b/r	b/r

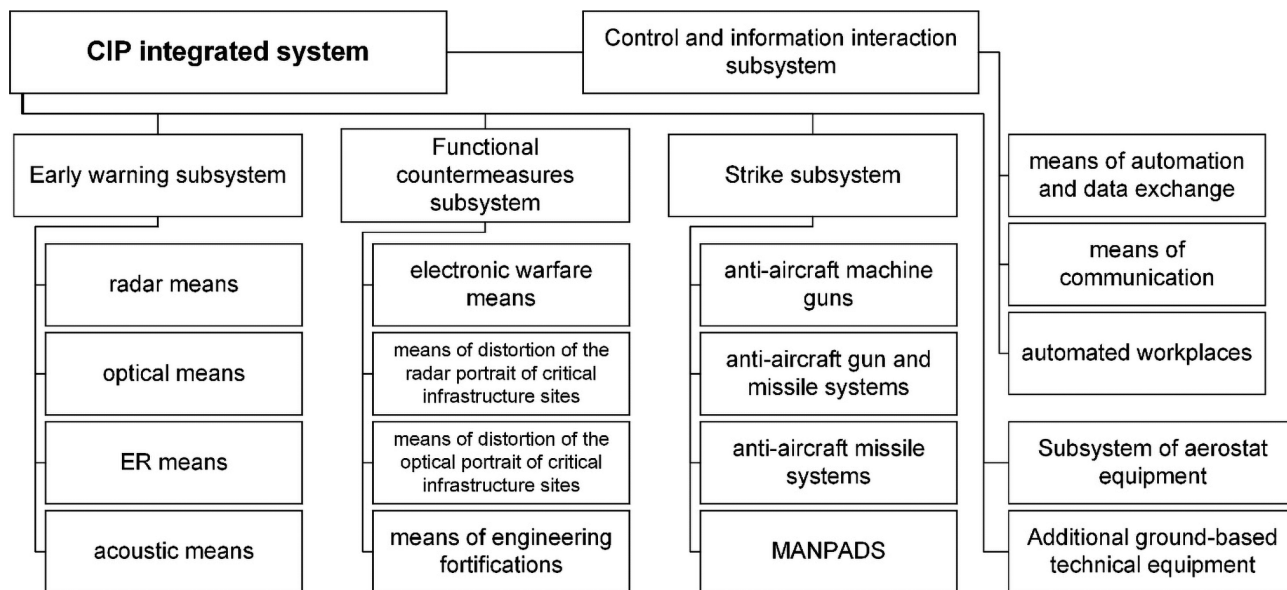


Fig. 4. Structure of the complex KI protection system

Additional means

As noted above, increasing the detection range of low-altitude anti-aircraft missiles can be achieved by installing radar on air balloon platforms. The aerostat equipment subsystem can also be used to install other means: optoelectronic, acoustic, ER and EW. In addition to the specified subsystems, the protection system should include traditional and special equipment (equipment, anti-aircraft defense, repair equipment, maintenance equipment, etc.).

The results of the study on the protection of the air defense system from enemy air attack indicate that the main areas of counteraction to the use of anti-aircraft missiles should include:

- information collection and processing measures, management of the enemy anti-aircraft missile counter-measure system;
- early detection of anti-aircraft missiles when approaching critical infrastructure facilities of Ukraine;
- measures of engineering and radio-electronic support of critical infrastructure facilities to protect against anti-aircraft missile strikes;
- measures of fire destruction of anti-aircraft missiles.

Thus, based on the results of the study, the composition of the complex protection system of the KI against enemy air attack attacks is proposed, which is shown in Fig. 4.

The essence of the functioning of the defense system: information about detected AAVs is summarized at the KI control and information interaction point, its processing and analysis are carried out, targeting is issued for means of electronic suppression and fire damage, electronic suppression and/or fire damage to the AAVs is carried out and control of the execution of tasks to avert danger is carried out. The specified cycle of work is carried out until the threat of damage to the critical infrastructure object is completely eliminated.

CONCLUSIONS

1. The results of the conducted research indicate that the existing capabilities for protecting critical infrastructure from AAVs strikes can be achieved by:

- improving the capabilities of detecting AAVs by installing sensors on high-altitude objects or balloons;
- increasing the quantitative composition of electronic warfare (EW) means (domestic and foreign production);
- developing domestic means of functional destruction of enemy cruise missiles using electromagnetic pulse weapons.

2. Simultaneously with the above measures, it is advisable to increase the level of protection of critical infrastructure objects from means of destruction through a complex of engineering and engineering and technical measures (masking in the optical and radar ranges, creating a false target environment, using initiative developments to interfere with airborne radio-electronic means of cruise missiles, etc.).

3. Work on arranging the positions of protection (defense) means, their final composition, performance characteristics and organization of interaction and information exchange measures require study in relation to the object of protection, taking into account its features.

4. The directions of further research can be defined as the extension of the proposed approaches to small-sized industrial facilities (taking into account their limited capabilities), as well as the computational formalization of the presented components and the study of the effectiveness of complex protection systems of various compositions.

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КОНЦЕПТУАЛЬНІ ОСНОВИ ПОБУДОВИ СИСТЕМИ КОМПЛЕКСНОГО ЗАХИСТУ ОБ'ЄКТІВ КРИТИЧНОЇ ІНФРАСТРУКТУРИ ВІД ПОВІТРЯНИХ ЗАГРОЗ

Основні дії противника вглибині країни спрямовані на знищення об'єктів критичної інфраструктури. Ефективний захист важливих об'єктів потребує комплексного підходу, а посадові особи повинні розуміти можливі способи і методи відвернення повітряних загроз для забезпечення живучості об'єктів захисту. Система комплексного захисту об'єкта критичної інфраструктури призначена для здійснення комплексу заходів щодо зниження імовірності ураження об'єкта внаслідок ударів засобів повітряного нападу. У статті представлені результати аналізу основних характеристик засобів повітряного нападу, зокрема дальності дії та маси бойової частини. Проведений комплекс досліджень показав невисокі значення ефективної поверхні розсіювання ударних засобів у радіолокаційному діапазоні. Представлені результати моделювання можливостей з виявлення, у тому числі при малошумних маршрутах руху. Для експлуатації в інтересах безпосереднього виявлення повітряних цілей та цілевказання мобільним вогневим групам проведено порівняльний аналіз можливостей малогабаритних РЛС. Запропоновано перелік засобів радіотехнічної розвідки для виявлення повітряних цілей та цілевказування засобам радіоелектронної боротьби. До складу підсистеми функціональної протидії запропоновано перелік засобів постановки радіоперешкод. Розглянуто засоби викривлення радіолокаційного та оптичного портрету, а також засоби маскування об'єктів захисту. Представлені варіанти оснащення підсистеми вогневого ураження. Для збільшення дальності виявлення малошумних повітряних цілей запропоновано встановлення радіолокаційних засобів на повітряних аеростатних платформах. Підсистема аеростатного спорядження також може використовуватися для встановлення оптико-електронних та акустичних засобів виявлення,

засобів радіотехнічної розвідки та радіоелектронної боротьби. За результатами проведеного дослідження запропоновано склад системи комплексного захисту об'єктів критичної інфраструктури від ударів засобів повітряного нападу.

Ключові слова: об'єкт критичної інфраструктури, система захисту, засоби повітряного нападу, виявлення, маскування, протидія повітряним загрозам.

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ANALYZING PLANAR ANTENNA ARRAYS FOR PERSPECTIVE AUTOMATED ELECTRONIC WARFARE STATIONS OPERATING AGAINST ON-BOARD RADAR SYSTEMS OF AIR ASSAULT MEANS

We claim that regarding electronic warfare systems there exists the problem of simultaneous providing large bandwidth, required directivity, quality of spatial signal filtering in interference background and resolution in angular coordinates. It is shown that solving this problem in conditions when computational resources are constrained is possible on the basis of exploiting antenna arrays in the form of Mills cross with Vivaldi elements and digital signal processing, at the same time providing respectively small weight and overall dimensions of antenna system. We develop the field pattern model of planar antenna array in the form of Mills cross that allow substantiating main technical requirements for both receiving and transmitting antenna systems of perspective electronic warfare systems operating against on-board radars of air assault means. We develop the simulation model of spatial signal filtering under interference influence for planar antenna array in the form of Mills cross with electronic control of antenna pattern and digital signal processing, allowing us determining characteristics of signal processing under interference conditions.

Keywords: planar antenna array, antenna array in the form of Mills cross, antenna array with digital signal processing, antenna pattern, directivity, bandwidth coefficient, Vivaldi element, radar system, electronic warfare against air assault means.

INTRODUCTION

Warding off armed aggression of Russian Federation and also the experience of local wars and armed conflicts of last decades earnestly testify to decisive role of air assault means (AAM) in reaching objectives of military operations and armed conflict as a whole. Main types of both tactical aviation planes and cruise missiles of armed forces of Russian Federation exploit modern radar on-board weapon control

systems, surveillance, low height flight safety insurance and navigation systems.

Actuality of developing perspective automated jamming station for electronic warfare (EW) against on-board radar systems is due to the necessity of providing air defence of corps and objects in military operations of Armed Forces of Ukraine, warding off both tactical aviation and cruise missiles strikes and also decreasing the efficiency of enemy air surveillance by means of jamming on-board radar systems of tactical aviation and cruise missiles.

As domestic and foreign analogues of perspective automated EW station operating against on-board radar systems of AAM we consider such jamming stations: SPN-40 (USSR, 1973), SPN-30 (USSR, 1975), SPN-2 (USSR, 1988), SPN-4 (USSR, 1989), Krasuha-2, Krasuha-4 (RF, 2012), Koral (Turkey, Aselsan, 2013), the appearance of some of them is shown in the Fig. 1. Aperture antennas (horn, reflector parabolic) are used as both receiving and transmitting antennas of automated jamming stations (AJS) SPN-40, SPN-30, Krasuha-2, Krasuha-4, whereas AJS SPN-2, SPN-4, Koral exploit antenna arrays.

There are a lot of requirements that are raised to antennas of modern electronic systems; among them three requirements have decisive importance. The first one is directivity, i.e. distribution of electromagnetic power in space (or response on arrived electromagnetic field when receiving the signals) according to some dependence. In some cases it is desired to provide omni-directional property of antenna, in others it is necessary to concentrate radiation or to receive the signals within rather narrow angle sector, i.e. main lobe of a field pattern of antenna system. The second and the third requirements mean that either transmitting or receiving the signals must provide maximal antenna efficiency, i.e. antenna has possess first, low voltage standing wave ratio (VSWR) and second, antenna radiation efficiency. As for EW systems, unlike other electronic systems, providing large respective bandwidth (BW) of frequency band (BW coefficient, i.e. the ratio maximal frequency of frequency band to minimal one) has an important significance, so that BW coefficient takes values from 3:1 and greater.

Known EW stations are usually supplied with log-periodic, spiral, biconical, discone and horn antennas providing BW coefficients that take values 10:1, 4:1, 4:1, 3:1 and 2:1, respectively. However, simultaneous providing contemporary requirements with respect to both wide frequency band, large directivity and respectively small weight and overall dimensions of antenna system is considered to be rather problematic.

The possible way of this problem solution is exploiting antenna arrays (including antenna arrays with digital signal processing) based on other technological principles.

BIBLIOGRAPHY ANALYSIS

Wideband antenna arrays based on Vivaldi elements are considered in works [1–7]. The approach to constructing wideband antennas developed on the basis of exploiting controlled coupled elements and also antenna arrays based on current sheet are considered in works [8–10]. Wideband antenna arrays with tightly coupled elements are considered in works [9–11]. The works [12–14, 16] investigate the

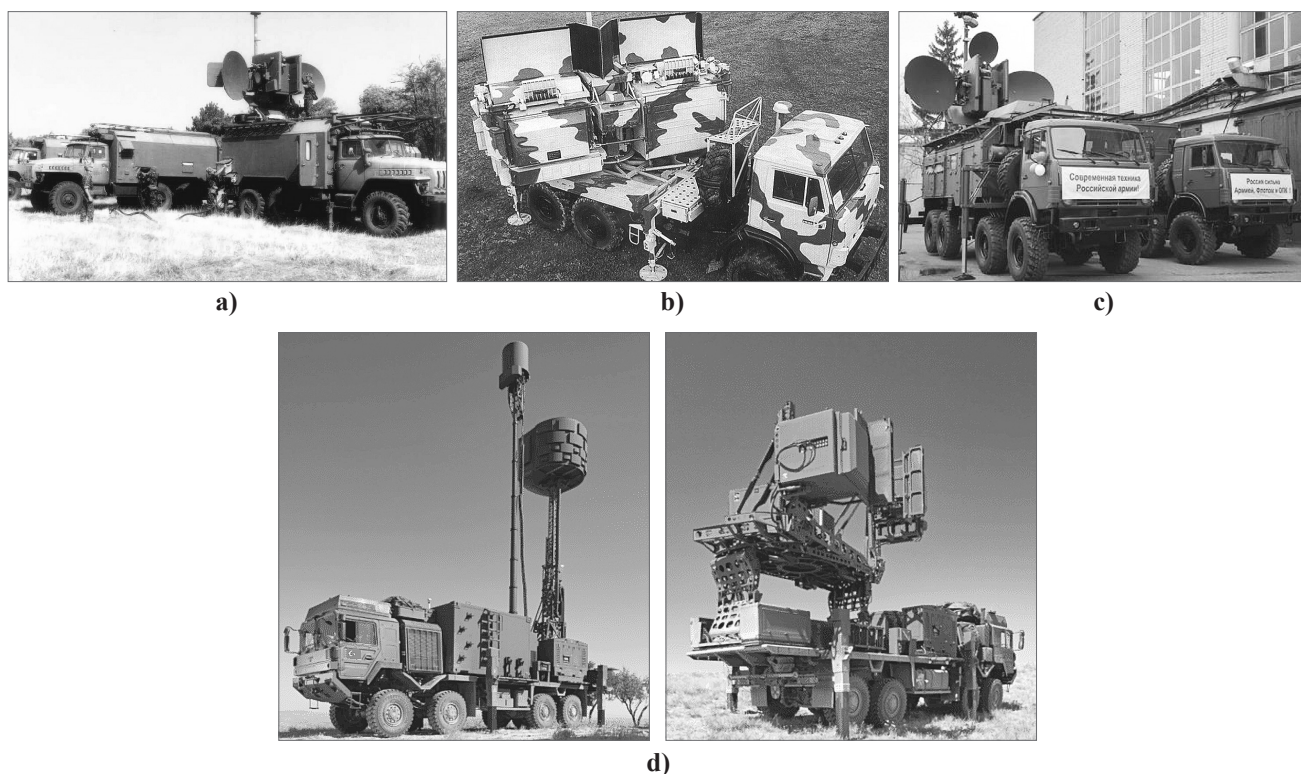


Fig. 1. AJS operating against on-board radar systems: a) SPN-30 (USSR); b) SPN-2 (USSR); c) Krasuha-4 (RF); d) Koral (Turkey, Aselsan)

problems of developing planar antenna arrays in the form of Mills cross, that allows sufficiently decreasing overall number of antenna elements with simultaneous preserving the required resolution in angular coordinates.

The objective of the article is first, developing the field pattern model of planar antenna array in the form of Mills cross on whose basis it is necessary to substantiate main technical requirements with respect to both receiving and transmitting antenna systems for perspective automated EW stations operating against on-board radar systems of AAM. **The second objective of the article** is developing the simulation model of spatial signal filtering under interference conditions for planar antenna array in the form of Mills cross with electronic control of antenna pattern and digital signal processing that allow determining an efficiency of signal processing in the presence of jam influence.

RESEARCH RESULTS

Vivaldi elements for wideband antenna arrays

Modern constructions of antenna arrays based on Vivaldi elements can provide VSWR lesser than 2 for relative frequency bandwidth (BW coefficient) 10:1 and even greater [1–7]. Almost ideal forms of antenna array pattern are provided at scanning angles (with respect to aperture normal) $\pm 50...60^\circ$. Antenna arrays based on Vivaldi elements designed and produced commercially do not require expensive materials to provide the aforementioned characteristics. Furthermore, antenna arrays based on Vivaldi elements contain in their structure the matching devices (transformers) that makes them compatible with widely used transmitting lines, e.g. microstrip lines.

Another name of antenna arrays based on Vivaldi elements is tapered slot antenna (TSA). Vivaldi name ta-

kes its origin from exponentially-slotted antenna that was first proposed in the work [4]. The development of TSA was being accomplished rather slowly up 1990-s, when numerical analysis methods realized by computers allow exactly describe characteristics of antenna arrays with a large number of elements. Just after that it was understood that successful design of wideband antenna arrays with electronic scanning is mainly based on modelling and inter-elements couple control.

Antenna arrays with electronic scanning and large aperture intended for simultaneous operating either in some wide frequency band or in some distant rather small frequency intervals must meet rough requirements with respect to main antenna characteristics that can be provided by antenna arrays based on Vivaldi elements. Arrays with single or dual polarization can be developed on the basis of TSA and operate within established characteristics in far-field zone.

To provide wide scanning sector without extra diffraction maximums of antenna array pattern in the form of relatively large side lobes, inter-element distance has not $0.5\lambda_{HF}$, where λ_{HF} is the wavelength at the highest frequency (HF) of the frequency band [1]. It is also known that diffraction theory recommends decreasing inter-element distance as far as possible to improve the possibilities of antenna pattern main lobe scanning.

The weight of TSA is mainly determined by the weight of dielectric material by which is filled the space between the elements. Maximum length of a typical element of TSA that operates in three octaves and more is equal to $8 \times 0.45\lambda_{HF}$. Hence one can calculate volume and weight of antenna array.

Fig. 2 illustrates the parameters defining TSA. All shown geometrical parameters affect the antenna efficiency but some common considerations can be used for improving antenna properties: 1) inter-element distances a, b along two coordinates x, y have to be $0.45\lambda_{HF}$; 2) usually the longest elements operate better at the lowest frequencies providing the wider frequency band; 3) thickness of dielectric substrate which is 0.1 of element width provides good results; 4) exponential parameter R_a and resonator diameter D_{sl} sufficiently affect the antenna properties.

Planar antenna arrays in the form of Mills cross

Planar antenna arrays in the form of Mills cross is a union of the elements of two linear antenna arrays arranged in two mutually orthogonal axes Ox, Oy [14]. The resulting process $y(t)$ in the output of antenna array in the form of Mills cross (Fig. 3a) is determined by the following expression:

$$y(t) = \sum_{n=1}^N \bar{w}_n^x a_n^x(t) + \sum_{m=1}^M \bar{w}_m^y a_m^y(t), \quad (1)$$

where $a_i^x(t), a_k^y(t)$ are the received signals in the inputs of i -th / k -th receiving element of linear antenna array (orthogonal component of planar array), whose elements are allocated along the axes Ox, Oy respectively; w_i^x, w_k^y are weight coefficients in i -th / k -th processing channel of antenna array, whose elements are allocated along the

axes Ox, Oy respectively; $\bar{w}_i = \text{Re}(w_i) - j \text{Im}(w_i)$; N, M are the numbers of antenna array along the axes Ox, Oy respectively.

A variant of joint allocation of 8...12 and 12...18 GHz band antenna arrays on the load-bearing slab for perspective AJS operating against on-board radar systems of AAM is shown in Fig. 3b.

Field pattern (FP) $F(\varphi, \theta)$ (or array factor) of planar antenna array is determined by the following equations [15; (2.45), (2.46)]:

$$F(\varphi, \theta) = F_0(\varphi, \theta) \sum_{m=1}^M \sum_{n=1}^N w_{mn} \cdot \exp \left[j2\pi \left\{ \begin{array}{l} (n-1) \frac{d_x}{\lambda} \\ (u-u_s) + \\ (m-1) \frac{d_y}{\lambda} \\ (v-v_s) \end{array} \right\} \right], \quad (2)$$

$$\begin{cases} u = \sin \theta \cos \varphi; \\ u_s = \sin \theta_s \cos \varphi_s, \end{cases} \quad \begin{cases} v = \sin \theta \sin \varphi; \\ v_s = \sin \theta_s \sin \varphi_s, \end{cases} \quad (3)$$

where N, M are numbers of the antenna array elements along the coordinate axes Ox, Oy respectively; d_x, d_y are inter-element distances along the coordinate axes Ox, Oy respectively; λ is a working wavelength; $F_0(\varphi, \theta)$ is a FP of a single Vivaldi element; φ_s, θ_s are FP main lobe angular coordinates controlled electronically; w_{mn} are complex

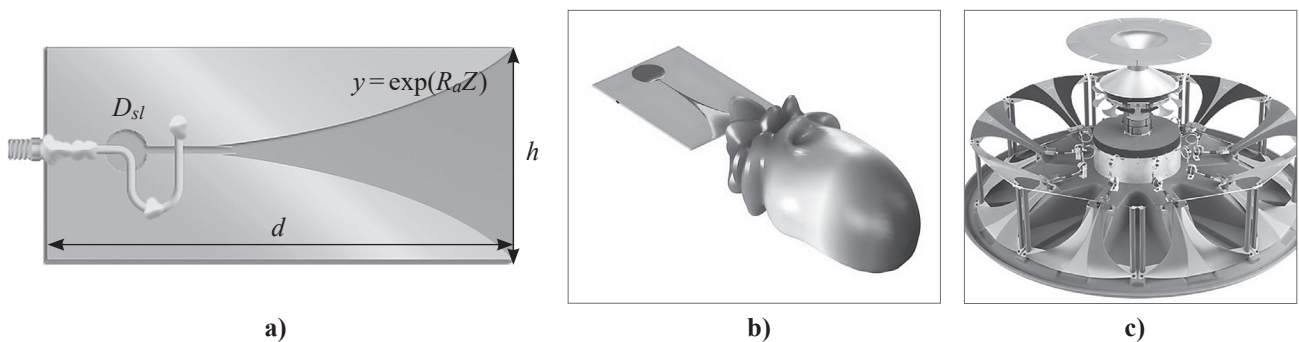


Fig. 2. Parameters of TSA: a) constructive parameters of the element; b) Vivaldi element field pattern; c) TSA of electronic support measures station TCI 903

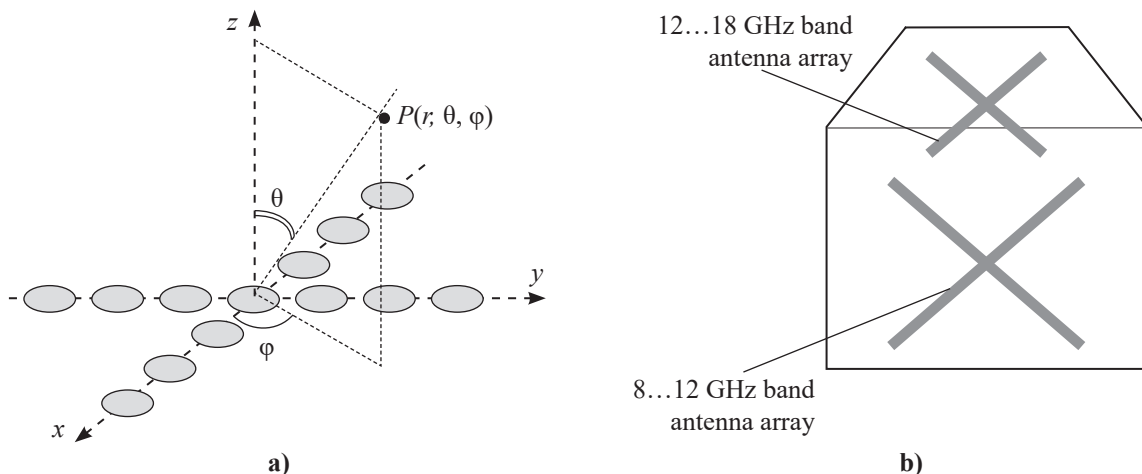


Fig. 3. Antenna arrays in the form of Mills cross for perspective AJS operating against on-board radar systems: a) common configuration within 3-D coordinate system; b) joint allocation of 8...12 and 12...18 GHz band antenna arrays on the load-bearing slab

weight coefficients used when realizing digital signal processing in antenna array.

Thus, from the expressions (1), (2), we obtain FP $F(\varphi, \theta)$ of antenna array in the form of Mills cross:

$$F(\varphi, \theta) = F_x(\varphi, \theta) + F_y(\varphi, \theta); \quad (4)$$

$$F_x(\varphi, \theta) = F_0(\varphi, \theta) \cdot \sum_{n=0}^{N-1} w_n \cdot \exp \left[j2\pi \left(n - \frac{N-1}{2} \right) \frac{d_x}{\lambda} (u - u_s) \right]; \quad (5)$$

$$F_y(\varphi, \theta) = F_0(\varphi, \theta) \cdot \sum_{m=0}^{M-1} w_m \cdot \exp \left[j2\pi \left(m - \frac{M-1}{2} \right) \frac{d_y}{\lambda} (v - v_s) \right]; \quad (6)$$

where the variables that are present in formulas (5), (6) have the same matter they have in the expressions (2), (3).

Fig. 4a, b illustrate the intersections of normalized FP of antenna arrays in the form of Mills cross with the numbers of elements that are equal to $2 \cdot 65 - 1$ and $2 \cdot 25 - 1$ respectively. These dependences were obtained on the basis of relationships (4)–(6) for azimuth coordinate plane. The width of FP $F_0(\varphi, \theta)$ of a single array element takes the value 120° for both azimuth and elevation planes measured at the level -3 dB with respect to maximum. The described variants of antenna arrays provide antenna gains 42.3 dB and 34 dB respectively. Inter-element distance takes the value $0.5\lambda_{HF}$, where λ_{HF} is a wavelength at the highest frequency HF of frequency band ($HF = 18$ GHz and 12 GHz for the

subbands $12 \dots 18$ and $8 \dots 12$ GHz respectively), so that main lobe width of FP takes the values 1.6° and 6° respectively measured at the level -3 dB with respect to maximum. It should be noted that at the lowest frequency LF of frequency band ($LF = 12$ GHz and 8 GHz for subbands $12 \dots 18$ and $8 \dots 12$ GHz respectively) one can notice widening main lobe FP up to the values 3° and 7.6° respectively at -3 dB with respect to maximum.

One of the main function of automatic target tracking subsystem of AJS is forming an error signal by exploiting the method of monopulse direction finding radiation emitter, i. e. on-board radar system of AAM. Fig. 5a, b illustrate the intersections of normalized FP of receiving antenna arrays in the form of Mills cross with the numbers of elements that are equal to $2 \cdot 65 - 1$ and $2 \cdot 25 - 1$ respectively while creating monopulse direction finding channels. These dependences were obtained on the basis of relationships (4)–(6) for azimuth coordinate plane. Partial FPs (conditionally left and right) are shown by the solid and dashed lines respectively, so that direction finding characteristic width takes the values 1.6° and 6° respectively at -3 dB with respect to maximum.

Electronically controlled main lobe of antenna array in the form of Mills cross

Here as both receiving and transmitting arrays we suppose exploiting antenna arrays with digital signal processing. In the case of mechanical method of FP main lobe scanning, the key parameters (antenna gain and FP width) provided by the given number of the elements ($2 \cdot 65 - 1$ and $2 \cdot 25 - 1$ respectively) remain quite satisfactory within the whole frequency band of AJS ($8 \dots 18$ GHz) (Fig. 4, 5). In the case

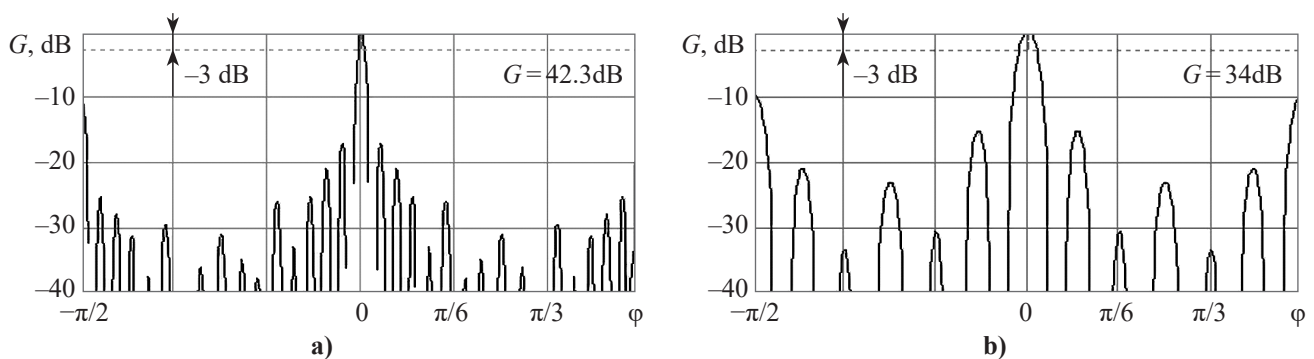


Fig. 4. Intersections of normalized FP of antenna arrays in the form of Mills cross: a) $2 \cdot 65 - 1$ elements antenna array; b) $2 \cdot 25 - 1$ elements antenna array

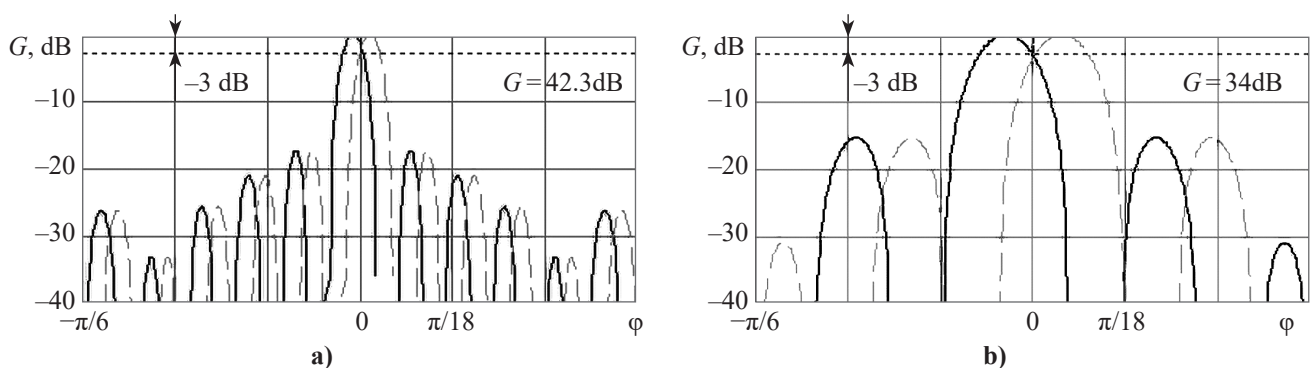


Fig. 5. Intersections of normalized FP of receiving antenna arrays in the form of Mills cross while creating monopulse direction finding channels: a) $2 \cdot 65 - 1$ elements antenna array; b) $2 \cdot 25 - 1$ elements antenna array

of electronic method of FP main lobe scanning, situation of providing these key parameters become worse. This fact is due to widening antenna array FP width while using frequencies that are close to LF of frequency subband ($LF = 12$ GHz and 8 GHz for subbands 12...18 and 8...12 GHz respectively).

Fig. 6 illustrate the intersections of normalized FP of antenna arrays in the form of Mills cross with the numbers of elements that are equal to $2 \cdot 65 - 1$ with electronic scanning the space in two coordinate planes. The positions of FP main lobe in both azimuth and elevation planes are determined by coordinates $\varphi_s = -\pi/3$; $\theta_s = \pi/4$ respectively and shown by the dashed line. The initial position of antenna array FP corresponding to coordinates $\varphi_s = 0$; $\theta_s = 0$ is shown by the solid line. In the Fig. 6a one can see that electronic scanning is accompanied by appearing parasitic mirror FP lobe which position is determined by coordinates $\varphi_- = \pi/3$; $\theta_- = \pi/4$, that negatively affect operating of both receiving and transmitting antenna arrays. In order to eliminate such a negative phenomenon it is necessary exploiting some measures, namely, creating «zero» FP at the direction of parasitic mirror FP lobe with $\varphi_- = -\varphi_s$ coordinate.

Fig. 7 illustrate the intersections of normalized FP of antenna arrays in the form of Mills cross with the numbers of elements that are equal to $2 \cdot 35 - 1$ with electronic scanning the space in two coordinate planes for the conditions that are similar to ones shown in Fig. 6.

It should be noted that situations concerning FP main lobe electronic scanning shown in Figs. 6, 7 correspond to such conditions: FP width $F_0(\varphi, \theta)$ (see formulas (5), (6)) of a single Vivaldi element takes the value 120° in both azimuth and elevation plane measured at the level

-3 dB with respect to maximum. The described variants of antenna arrays provide antenna gain 42.3 dB and 36.9 dB respectively. Inter-element distance takes the value $0.5\lambda_{HF}$, where λ_{HF} is a wavelength at the highest frequency HF of frequency subband ($HF = 18$ GHz and 12 GHz for the subbands 12...18 and 8...12 GHz respectively), so that FP main lobe width takes the values 1.6° and 4° respectively measured at the level -3 dB with respect to maximum. It should be noted that at the lowest frequency LF of a subband ($LF = 12$ GHz and 8 GHz for the subbands 12...18 and 8...12 GHz respectively) one can notice widening main lobe FP up to the values 5.1° and 9.8° respectively at the level -3 dB with respect to maximum.

Eliminating parasitic mirror FP lobe in the case when main lobe position is determined by coordinates $\varphi_s = \pi/3$; $\theta_s = \pi/4$, shown in Figs. 6a and 7a for antenna arrays with $2 \cdot 65 - 1$ and $2 \cdot 35 - 1$ elements, by creating «zero» FP at the direction of parasitic mirror FP lobe with coordinate $-\varphi_s$ is realized on the basis of the known relationship [15; (2.45), (2.46)]:

$$F_c(\varphi, \theta) = F(\varphi, \theta)|_{\varphi_s} - \gamma \cdot F(\varphi - \varphi_-, \theta)|_{\varphi_s=0}, \quad (7)$$

where $F_c(\varphi, \theta)$ is corrected FP of antenna array; $F(\varphi, \theta)|_{\varphi_s=0}$ is initial FP (without steering angles: $\varphi_s = 0$; $\theta_s = 0$); $F(\varphi, \theta)|_{\varphi_s}$ is FP as $\varphi_s \neq 0$ without compensation of receiving in the direction of parasitic mirror FP lobe (see Fig. 6a and 7a); γ is the level of parasitic mirror FP lobe; φ_- is the direction of parasitic mirror FP lobe: $\varphi_- = -\varphi_s$.

Fig. 8a,b illustrate the resulting corrected FPs $F_c(\varphi, \theta)$ (see formula (7)) for antenna arrays in the form of Mills cross with electronic scanning in azimuth plane (FP main lobe $\varphi_s = -\pi/3$) and suppressing parasitic mirror FP lobe

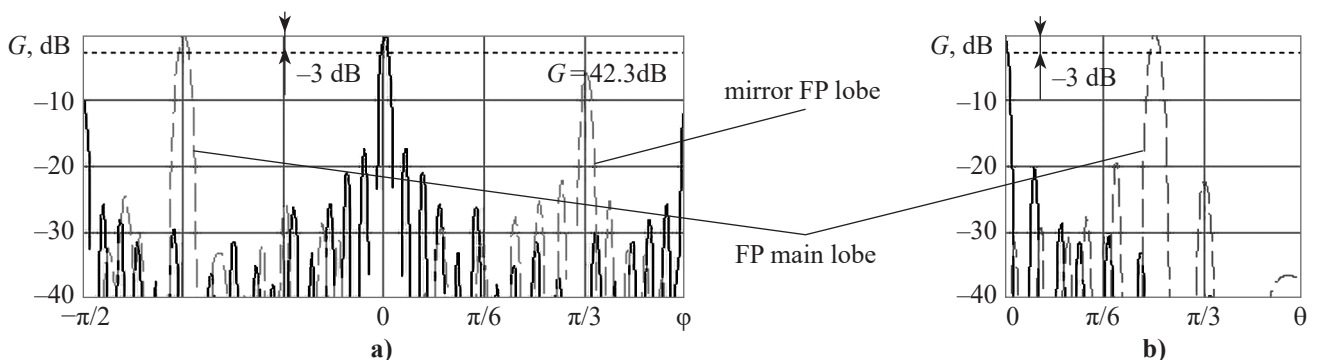


Fig. 6. Intersections of normalized FP of antenna arrays in the form of Mills cross ($2 \cdot 65 - 1$ elements) with electronic scanning: a) in azimuth plane (FP main lobe $\varphi_s = -\pi/3$); b) in elevation plane (FP main lobe $\theta_s = \pi/4$)

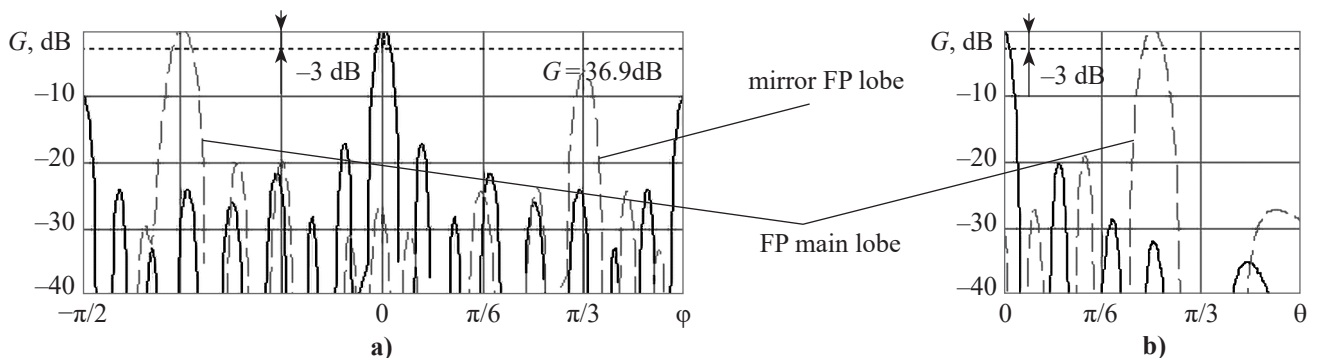


Fig. 7. Intersections of normalized FP of antenna arrays in the form of Mills cross ($2 \cdot 35 - 1$ elements) with electronic scanning: a) in azimuth plane (FP main lobe $\varphi_s = -\pi/3$); b) in elevation plane (FP main lobe $\theta_s = \pi/4$)

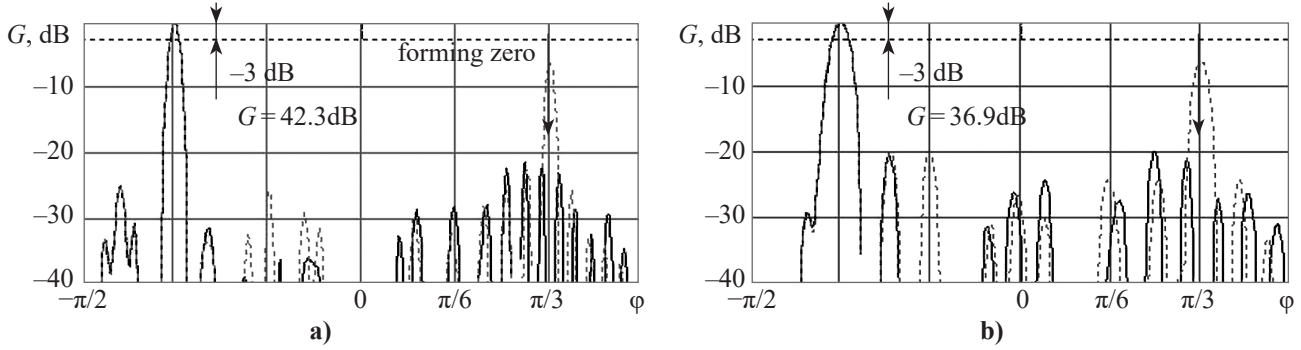


Fig. 8. Intersections of normalized FP of antenna arrays in the form of Mills cross with electronic scanning in azimuth plane (FP main lobe $\varphi_s = -\pi/3$) and suppressing parasitic mirror FP lobe ($\varphi = \pi/3$): a) array with $2.65 - 1$ elements; b) array with $2.35 - 1$ elements

($\varphi = \pi/3$) with number of elements that are equal to $2.65 - 1$ and $2.35 - 1$ correspondingly. The corrected FPs $F_c(\varphi, \theta)$ are shown by solid line, whereas FPs $F(\varphi, \theta)|_{\varphi_s}$ without compensating reception at the direction to parasitic mirror FP lobe are shown by dotted line.

Spatial signal filtering under interference conditions in wideband antenna array in the form of Mills cross

Consider the problem of spatial filtering a narrowband useful signal that is solved by a wideband antenna array in the form of Mills cross (Fig. 3a) consisting of $2N - 1$ elements (where N is an odd number). We investigate an antenna array with a ratio $f_{\max} / f_{\min}$ maximum to minimum frequencies of processed signals that belong to the interval $f_{\max} / f_{\min} \in [1.1, 2.0]$.

Let $a_i^{x,y}(t)$ be an additive mixture (see formula (1)) observed in the input of i -th element of antenna array orthogonal component (x or y) consisting of useful signal $s(t)$, L complex narrowband interference signals $u_l(t)$, each of them is coming from l -th point emitter, and complex quasi-white Gaussian noise $n(t)$ with zero mean:

$$\begin{aligned} a_i^{x,y}(t) &= s_i(t) + \sum_{l=1}^L u_{l,i}(t) + n_i(t) = \\ &= s(t, \omega_s) \exp \left(-j2\pi \frac{f_s}{f_0} \frac{d}{\lambda_0} \left(i - \frac{N+1}{2} \right) \sin \theta_s \begin{Bmatrix} \cos \varphi_s \\ \sin \varphi_s \end{Bmatrix} \right) + \\ &+ \sum_{l=1}^L u_l(t, \omega_l) \exp \left(-j2\pi \frac{f_l}{f_0} \frac{d}{\lambda_0} \left(i - \frac{N+1}{2} \right) \sin \theta_l \begin{Bmatrix} \cos \varphi_l \\ \sin \varphi_l \end{Bmatrix} \right) + \\ &+ n_i(t) \end{aligned} \quad (8)$$

where $t = t_m = t_0 + m \cdot \Delta t$; $m = 0, 1, \dots, M - 1$; Δt is a sampling interval of the signals; $s_i(t)$ is the useful signal $s(t)$ observed in i -th channel of antenna array; $\omega_s = 2\pi f_s = \text{const}$, f_s is a carrier frequency of the useful signal $s(t)$; (θ_s, φ_s) are the directions of arrival of the signal $s(t)$; (θ_l, φ_l) are the directions of arrival of the interference signal $u_{l,i}(t)$; $\omega_l = 2\pi f_l = \text{const}$, f_l is a carrier frequency of the interference signal $u_{l,i}(t)$ received in the i -th channel of antenna array; the frequencies $\{f_l\}$ of the signals $\{u_l(t)\}$ and the carrier frequency f_s of the useful signal $s(t)$ are different and distributed in some interval: $f_l, f_s \in [f_{\min}, f_{\max}]$, $f_0 \leq f_{\min}$, $f_{\max} / f_{\min} \in [1.1, 2.0]$; $n_i(t) = n_i^c(t) + j \cdot n_i^s(t)$ is a noise observed in the i -th channel of antenna array, $j = \sqrt{-1}$; $\mathbf{M}\{u_l(t)u_k(t)\} = 0$, $l \neq k$; $\mathbf{M}\{n_i(t)n_j(t)\} = 0$, $i \neq j$; $\mathbf{M}\{*\}$ is the symbol of mathematical expectation; $\mathbf{M}\{(n_i^c(t))^2\} = \mathbf{M}\{(n_i^s(t))^2\} = D_n / 2$, D_n is a

variance of quasi-white Gaussian noise $n_i(t)$ with zero mean; d is inter-element distance of antenna array, $d = 0.5\lambda_0$, where λ_0 is the wavelength corresponding to the minimal frequency of the processed signals $f_0 \leq f_{\min}$.

The resulting process $y(t)$ in the output of signal processing unit of antenna array in the form of Mills cross consisting of $2N - 1$ elements (see Fig. 3a) is defined by weighted sum of delayed signal copies $a_i(t)$ in the receiving channels [15; (10.17)], [16; (61.2)]:

$$z(t) = \sum_{i=1}^N \sum_{k=0}^{K-1} [\bar{w}_{i,k}^x \cdot a_i^x(t - \Delta_k) + \bar{w}_{i,k}^y \cdot a_i^y(t - \Delta_k)], \quad (9)$$

where $t = t_m = t_0 + m \cdot \Delta t$; $m = 0, 1, \dots, M - 1$; Δt is a sampling interval of the signals; $a_i^{x,y}(t)$ is the received signal in the input of i -th receiving element of antenna array orthogonal component (see formula (8)); $w_{i,k}$ is weight coefficient in the i -th processing channel in the output of k -th delay element; $\bar{w}_{i,k} = \text{Re}(w_{i,k}) - j \text{Im}(w_{i,k})$; Δ_k is a value of signal delay in the output of k -th delay element, $\Delta_{k=0} = 0$, $\Delta_k < \Delta_{k+1}$; K is a number of delay elements in each channel.

According to spatial filtering algorithm (9), on the basis of observations $a_i^{x,y}(t)$ in the input of i -th antenna array element (8) it is necessary to form $M \times 2N$ input signals matrix

$$\mathbf{a} = \|\mathbf{a}_{m,i}\| = \begin{bmatrix} a_1^x(t_0) & \dots & a_N^x(t_0) & a_1^y(t_0) & \dots & a_N^y(t_0) \\ a_1^x(t_1) & \dots & a_N^x(t_1) & a_1^y(t_1) & \dots & a_N^y(t_1) \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ a_1^x(t_{M-1}) & \dots & a_N^x(t_{M-1}) & a_1^y(t_{M-1}) & \dots & a_N^y(t_{M-1}) \end{bmatrix},$$

including signal samples $a_i^{x,y}(t)$ and their delayed on Δ_k copies, so that the resulting matrix involving these matrices takes the following form:

$$\mathbf{A} = \|\mathbf{A}_{m,l}\| = \text{augment}(\mathbf{A}_0, \mathbf{A}_1, \dots, \mathbf{A}_{K-1}); \quad (10)$$

$$\mathbf{A}_k = \|\mathbf{a}_{m,i}\|; \mathbf{A}_0 = \mathbf{a}; a_{m,i} = a_i(t_m - \Delta_k), \quad (10a)$$

where $\text{augment}(\mathbf{A}, \mathbf{B}, \mathbf{C}, \dots)$ is the function that returns an array formed by placing matrices $\mathbf{A}, \mathbf{B}, \mathbf{C}, \dots$ left to right; $t = t_m = t_0 + m \cdot \Delta t$; $m = 0, 1, \dots, M - 1$; $i = 1, 2, \dots, 2N$; $k = 0, 1, \dots, K - 1$; $l = 1, 2, \dots, 2N \cdot K$; $\Delta_{k=0} = 0$, $\Delta_k < \Delta_{k+1}$.

Thus, matrix $\mathbf{A}$ has a size $M \times (2N \cdot K)$, where M is a number of temporal samples of the signal $a_i(t)$ used in processing; $2N - 1$ is a number of elements of antenna array in the form of Mills cross; K is a number of delayed elements

in each channel. Then the estimator $\hat{\mathbf{R}}_a$ of correlation matrix $\mathbf{R}_a$ that is formed on the basis of observations (8) has the size $(2N \cdot K) \times (2N \cdot K)$:

$$\hat{\mathbf{R}}_a = \left\| R_{r,c}^a \right\| = \frac{1}{M} \left\| \left(\mathbf{A}^{<r>} \right)^T \overline{\mathbf{A}^{<c>}} \right\|, \quad (11)$$

where $r=1, \dots, 2N \cdot K$; $c=1, \dots, 2N \cdot K$; $\mathbf{A}^{<c>}$ is a vector formed on the basis of c -th column of the matrix $\mathbf{A}$ (10); $\overline{\mathbf{A}^{<c>}}$ is complex conjugate to $\mathbf{A}^{<c>}$; M is a number of temporal samples of the signals $a_i^{x,y}(t)$ used in signal processing.

Antenna array operating on the basis of minimum variance criterion provides optimal solution for vector of weight coefficients $\mathbf{w}$ in the following form [15; (3.117)], [17; (61.18)]:

$$\mathbf{w} = [w_1, \dots, w_{2N \cdot K}]^T = \frac{\hat{\mathbf{R}}_a^{-1} \mathbf{E}(\theta_s, f_s)}{\mathbf{E}(\theta_s, f_s)^T \hat{\mathbf{R}}_a^{-1} \mathbf{E}(\theta_s, f_s)}; \quad (12)$$

$$\begin{aligned} \mathbf{E}(\theta_s, \varphi_s, f_s) &= \text{stack}[\mathbf{e}(\theta_s, \varphi_s, f_s), \\ &\mathbf{e}(\theta_s, \varphi_s, f_s) \cdot \exp(-j2\pi f_s \cdot \Delta_1), \dots; \quad (13a) \\ &\dots, \mathbf{e}(\theta_s, \varphi_s, f_s) \cdot \exp(-j2\pi f_s \cdot \Delta_{K-1})] \end{aligned}$$

$$\mathbf{e}(\theta_s, \varphi_s, f_s) = \text{stack}(\mathbf{e}_x(\theta_s, \varphi_s, f_s), \mathbf{e}_y(\theta_s, \varphi_s, f_s)); \quad (13b)$$

$$\mathbf{e}_{x,y}(\theta_s, \varphi_s, f_s) = \begin{bmatrix} \exp \left(-j2\pi \frac{f_s}{f_0} \frac{d}{\lambda_0} \left(i - \frac{N+1}{2} \right) \right) \\ \sin \theta_s \begin{Bmatrix} \cos \varphi_s \\ \sin \varphi_s \end{Bmatrix} \end{bmatrix}, \quad (13c)$$

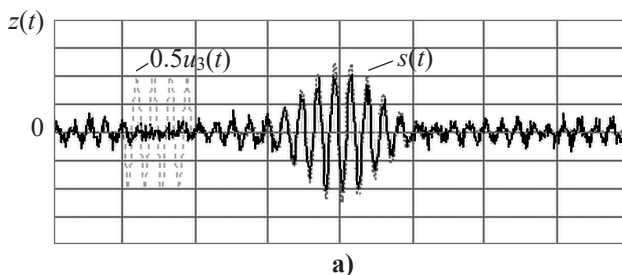
where $\hat{\mathbf{R}}_a$ is the estimator of correlation matrix $\mathbf{R}_a$ (11) of the observations; $\mathbf{e}(\theta_s, \varphi_s, f_s)$ is vector of complex spatial harmonics (steering vector) as a function of angles of signal arrival (θ_s, φ_s) and carrier frequency f_s of the signal $s(t)$; $\mathbf{e}_x(\theta_s, \varphi_s, f_s)$, $\mathbf{e}_y(\theta_s, \varphi_s, f_s)$ are the vectors of complex spatial harmonics for orthogonal components of planar antenna array in the form of Mills cross; $\mathbf{E}(\theta_s, \varphi_s, f_s)$ is a modified vector of complex spatial harmonics (steering vector); $\text{stack}(\mathbf{A}, \mathbf{B}, \mathbf{C}, \dots)$ is the function that returns an array formed by placing matrices $\mathbf{A}, \mathbf{B}, \mathbf{C}, \dots$ top to bottom.

The considered algorithm (9)...(13) is illustrated by an example that is realized by simulation modelling this algorithm.

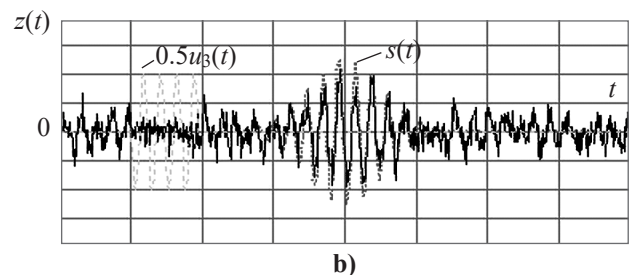
Example. Assume that in the inputs of wideband planar antenna array in the form of Mills cross consisting of $2 \cdot 35 - 1$ elements we observe an additive mixture (8) consisting of the useful signal $s(t)$ coming from the direction $(\theta_s, \varphi_s) = (\pi/4, -\pi/3)$, interference signals $u_1(t)$, $u_2(t)$, $u_3(t)$, $u_4(t)$,

$u_5(t)$ arriving from the directions $(\theta_1, \varphi_1) = (2\pi/9, -3\pi/8)$; $(\theta_2, \varphi_2) = (4\pi/13, \pi/10)$; $(\theta_3, \varphi_3) = (\pi/3, 3\pi/14)$; $(\theta_4, \varphi_4) = (3\pi/7, 7\pi/18)$; $(\theta_5, \varphi_5) = (2\pi/5, -3\pi/14)$ correspondingly and also uncorrelated quasi-white Gaussian noise $n(t)$, that affects in the receiving channels of antenna array. Interference signals $u_1(t)$ and $u_2(t)$ are amplitude-modulated and frequency-modulated jams respectively; interference signal $u_3(t)$ is a radio-frequency pulse with rectangular envelope and uncorrelated interference signals $u_4(t)$, $u_5(t)$ are quasi-white Gaussian noises. Signal to k -th interference ratios in a single i -th receiving channel of antenna array take the values that are equal to 0.25; 0.25; 1; 0.05; 0.05 respectively. Signal to noise ratio takes the value 30 dB. Signal to resulting interference ratio took the value -10 dB. The frequencies of received interference signals as well as the frequency of useful signal are distributed in some interval: $[f_{\min}, f_{\max}]$, $f_0 \leq f_{\min}$, $f_{\max} / f_{\min} \approx 1.5$; inter-element distance of antenna array is equal to $d = 0.5\lambda_0$, where λ_0 is a wavelength corresponding to minimal frequency of the processed signals $f_0 \leq f_{\min}$. The signal delay values Δ_k in the receiving channels (9) are chosen to be equal to $\Delta_k = 0; 1\Delta t; 3\Delta t; 4\Delta t; 5\Delta t$, $\Delta t = 1/(2f_{\max})$. The number of samples M of signals $a_i^{x,y}(t)$ used in processing is chosen to be equal to $M = 1024$.

Fig. 9a,b illustrate estimates $z(t) = \hat{s}(t)$ of useful signal $s(t)$ that are formed according to spatial filtering algorithm (9)...(13) based of correlation matrix estimator (11), so that the results are shown for the cases of both mechanic and electronic scanning FP main lobe respectively. The difference in signal processing within the framework of general algorithm (9)...(13) lies in the fact that while controlling mechanically the antenna array is considered to be adjusted for the direction of arrival of useful signal so that the vectors of complex spatial harmonics $\mathbf{e}_x(\theta_s, \varphi_s, f_s)$, $\mathbf{e}_y(\theta_s, \varphi_s, f_s)$ figuring in the formula (13c) are unitary: $\mathbf{e}_x(\theta_s, \varphi_s, f_s) = [1, 1, \dots, 1]^T$, $\mathbf{e}_y(\theta_s, \varphi_s, f_s) = [1, 1, \dots, 1]^T$. Coefficients of interference suppression for the first and the second variants of signal processing took the values $K_z = 40 \dots 45$ dB and $35 \dots 39.4$ dB respectively. Here coefficient of interference suppression is defined as the ratio $K_z = 10 \lg(D_J / D[z(t) - s(t)])$, where D_J is a variance of resulting interference, $D_J = \sum_{l=1}^L D_l$, D_l is a variance of l -th interference; $D[z(t) - s(t)]$ is a variance of a noise component of the process $z(t)$ in the output of signal processing unit. Both figures illustrate the position of pulse interference $u_3(t)$ that is shown twice smaller in amplitude. As one can see



a)



b)

Fig. 9. Estimates $z(t) = \hat{s}(t)$ of useful signal $s(t)$ that are formed according to spatial filtering algorithm (9)...(13) in planar antenna array in the form of Mills cross consisting of $2 \cdot 35 - 1$ elements for the cases:

a) mechanic scanning FP main lobe; b) electronic scanning FP main lobe

from the figures, amid the same interference environment, antenna array that is adjusted for the useful signal receiving (steering vectors from (13c) are unitary) provides better spatial filtering (~5 dB) than array with electronic scanning the space.

CONCLUSIONS

1. Solving the problem of substantiating contemporary requirements for AJS operating against on-board radar systems of AAM concerning simultaneous providing wide frequency band, large directivity and small both weight and size parameters is possible by exploiting wideband planar antenna arrays built on the basis of new technological principles, namely, basing on exploiting new wideband elements for antenna arrays and also digital signal processing in both receiving and transmitting antenna arrays.

2. Main types of wideband planar antenna arrays built on new technological principles that can be exploited when developing perspective EW stations, are antenna arrays based on Vivaldi elements.

3. Providing wide frequency band, high quality of spatial signal filtering amid interference influence, high directivity and required resolution over angular coordinates while minimizing a number of antenna array elements and hence minimizing the required calculation recourses, is possible on the basis of antenna arrays in the form of Mills cross with Vivaldi elements and digital signal processing.

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АНАЛІЗ МОЖЛИВОСТЕЙ ВИКОРИСТАННЯ ПЛАНАРНИХ АНТЕННИХ РЕШІТОК У ПЕРСПЕКТИВНИХ ЗРАЗКАХ ТЕХНІКИ РАДІОЕЛЕКТРОННОЇ БОРОТЬБИ З БОРТОВИМИ РАДІОЛОКАЦІЙНИМИ СИСТЕМАМИ ЗАСОБІВ ПОВІТРЯНОГО НАПАДУ

Стверджується, що для систем радіоелектронної боротьби характерна проблема одночасного забезпечення значного діапазону робочих частот, потрібних коефіцієнту направленої дії, якості просторової фільтрації сигналів на фоні перешкод і розрізняювальної здатності по кутових координатах. Показується, що вирішення цієї проблеми при обмежених обчислювальних ресурсах можливо шляхом застосування антенних решіток з цифровою обробкою сигналів у вигляді хреста Мілса на елементах Вівальді, при цьому забезпечуються відносно невеликі масо-габаритні показники антенної системи. Розроблено модель діаграми направленості планарної антенної решітки у вигляді хреста Мілса, на основі якої обґрунтовано основні технічні характеристики до приймальних і передавальних антенних систем перспективних засобів радіоелектронної боротьби з бортовими радіолокаційними системами засобів повітряного нападу. Розроблено модель просторової фільтрації сигналів на фоні перешкод для планарної антенної решітки у вигляді хреста Мілса з електронним способом управління головним променем діаграми направленості та цифровою обробкою сигналів, на основі якої визначено характеристики обробки корисних сигналів в умовах впливу перешкод.

Ключові слова: планарна антенна решітка, антенна решітка у вигляді хреста Мілса, антенна решітка з цифровою обробкою сигналів, діаграма направленості, коефіцієнт направленої дії, коефіцієнт широкосмуговості, елемент Вівальді, радіолокаційна

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ПРАКТИЧНІ АСПЕКТИ РОЗГОРТАННЯ ВЕЛИКИХ МОВНИХ МОДЕЛЕЙ В ЛОКАЛЬНИХ МЕРЕЖАХ

У статті розглядаються практичні аспекти розгортання великих мовних моделей (LLM) у локальних мережах для обробки конфіденційної інформації. Автори аналізують можливості фреймворків, таких як LM Studio, Ollama, Anything LLM та Koboldcpp, у різних сценаріях архітектури клієнт-сервер. Особливу увагу приділено функціональним обмеженням, технічним нюансам налаштування, а також ефективності й безпеці використання систем для вирішення завдань у військовій та науковій сферах. Зокрема, описано комбінацію фреймворків Anything LLM та Ollama, яка забезпечує інтеграцію з базами знань через механізм Retrieval-Augmented Generation (RAG), дозволяючи організувати захищену обробку даних у локальному середовищі.

Викладено переваги архітектури на базі фреймворку Koboldcpp, що підтримує кастомізацію моделей та інтеграцію з GPU для прискорення обчислень. Розглянуто проблеми, які виникають при використанні LM Studio для створення серверної інфраструктури через обмежену функціональність API та складнощі з налаштуванням доступу. Наголошується, що оптимальним вибором для локального розгортання LLM у клієнт-серверній архітектурі є поєднання Anything LLM як інтерфейсу користувача та Koboldcpp як серверної платформи. Така система забезпечує гнучкість, економію ресурсів і високу захищеність даних, що особливо важливо для застосувань у сфері національної безпеки.

Ключові слова: локальні великі мовні моделі, обробка конфіденційної інформації, клієнт-серверна архітектура, фреймворки LLM, локальна мережа, Retrieval-Augmented Generation, безпека даних, налаштування серверів.

ВСТУП

Запропонована в [1] загальна концепція застосування локальних великих мовних моделей (LLM) типу GPT-4o [2] та O1 від OpenAI [3] для обробки конфіденційної інформації досить просто реалізується при розгортанні LLM за допомогою спеціальних фреймворків типу LM Studio [4], Ollama [5] та ін. Їх дослідна експлуатація,

проведена авторами в інтересах технічних перекладів, підготовки звітів і виконання інших завдань у сфері розвитку озброєння та військової техніки, засвідчила свою ефективність.

Сценарій, коли доступ користувача до LLM здійснюється без використання серверних спроможностей фреймворків, є найбільш доступним для втілення. Дещо складнішим стає варіант серверного доступу до LLM, який потребує певних попередніх налаштувань, однак в режимі Localhost його забезпечують майже всі зазначені фреймворки. Нюанси виникають, коли для подолання обмеженості обчислювальних ресурсів конкретного комп'ютерного обладнання потрібно рознести у просторі користувача і сервер з LLM в рамках локальної мережі з організацією доступу до LLM з клієнтських терміналів. Крім проблем адміністрування локальної мережі, у такому випадку виникають й інші практичні питання, оскільки, як виявилось, не всі LLM-фреймворки можуть бути задіяні для реалізації такої архітектури. Окрім функціональних обмежень, додатковою складністю є сумісність різних фреймворків, оскільки не всі з них підтримують архітектуру клієнт-сервер у локальних мережах, що вимагає тестування і перевірки можливості взаємодії між ними у вибраному сценарії.

Мета статті полягає у дослідженні особливостей розгортання локальних великих мовних моделей (LLM) для обробки конфіденційної інформації з акцентом на різні архітектурні рішення та інструменти реалізації. Зокрема, стаття буде зосереджена на аналізі сценаріїв, коли доступ до LLM здійснюється в рамках клієнт-серверної архітектури у локальній мережі. Особлива увага приділятиметься порівнянню можливостей фреймворків, таких як LM Studio, Ollama, Anything LLM [6] та ін., в контексті їх здатності підтримувати віддалений доступ до LLM, а також розгляду технічних нюансів, що виникають при їх використанні для забезпечення надійності та безпеки обробки даних.

АРХІТЕКТУРА «КЛІЄНТ-СЕРВЕР» НА ОСНОВІ КОМБІНАЦІЇ ФРЕЙМВОРКІВ ANYTHING LLM ТА OLLAMA

Ефективний підхід для розгортання локальних LLM з можливістю віддаленого доступу до них в локальній мережі полягає у використанні комбінації фреймворків Anything LLM [6] та Ollama [5] у сценарії клієнт-сервер. На рис. 1 представлено загальну архітектуру такої системи, що використовує комбінацію фреймворку Anything LLM та серверної платформи Ollama для розгортання LLM у клієнт-серверному середовищі з додатковою підтримкою Retrieval-Augmented Generation (RAG) [7]. Архітектура системи поділена на кілька функціональних блоків: апаратне забезпечення та мережева інфраструктура, програмне забезпечення, а також модуль RAG, який забезпечує інтеграцію з базами знань та конфіденційних документів.

Апаратне забезпечення та мережева інфраструктура включають сервери Ollama, оснащені процесорами (CPU) та графічними процесорами (GPU) для забезпечення ефективної роботи LLM. Сервери підключені до локальної мережі (LAN), що дозволяє авторизованим

користувачам отримувати доступ до системи. Для підвищення рівня безпеки використовується сегментація мережі, що забезпечує ізоляцію різних компонентів системи та контролює доступ між ними.

Програмне забезпечення представлено інтерфейсом користувача, який реалізовано за допомогою фреймворку Anything LLM, що забезпечує взаємодію користувачів з моделлю LLaMa-3.1-8B [8]. Інтерфейс дозволяє користувачам, які працюють на робочих станціях, надсилати запити до LLM та дистанційно отримувати результати обробки відповідних інструкцій.

Для зберігання даних використовується сховище на основі швидкісних накопичувачів SSD, яке гарантує швидкий доступ до необхідних файлів. За потреби, для роботи з моделлю LLaMa-3.1-8B можуть бути використані фреймворки глибокого навчання, такі як PyTorch та TensorFlow, для забезпечення ефективних обчислень та донавчання LLM на документах користувачів.

Retrieval-Augmented Generation (RAG) включає модуль інтеграції, який забезпечує взаємодію моделі LLM із зовнішніми базами знань. Механізм пошуку (Retriever) використовується для отримання релевантної інформації з загальної бази знань або персональної бази знань, яка може містити специфічну інформацію, необхідну для більш точного контекстного аналізу [7]. Це дозволяє моделі генерувати більш релевантні та обґрунтовані відповіді на запити користувачів. Такий підхід дозволяє організувати обробку конфіденційної інформації, забезпечуючи при цьому гнучкість в управлінні доступом та масштабованість системи. Розглянемо детальніше, як можна налаштувати та інтегрувати зазначені фреймворки для досягнення цієї мети.

Серверна частина системи передбачає розгортання Ollama, що відповідає за локальну роботу LLM, використовуючи ресурси серверу, зокрема GPU та CPU, для ефективної обробки запитів. Серверна компонента додатково налаштовується за допомогою фреймворку Anything LLM, що дозволяє управляти моделлю, обробляти запити та відправляти відповіді клієнтам на основі графічного інтерфейсу. Користувачі отримують доступ до LLM через клієнтську частину, яка підключається до серверу за допомогою локальної мережі, використовуючи IP-адресу сервера та визначений порт. Запити від клієнтів вводяться через діалоговий інтерфейс чату з LLM,

що інтегрований до Anything LLM. Далі цей фреймворк виконує функції маршрутизації, забезпечення безпеки та передачі запиту до Ollama, яка обробляє їх, використовуючи LLM, і повертає відповідь клієнтам. Взаємодія між клієнтом та сервером може здійснюватися у форматі JSON, що дозволяє легко обробляти та використовувати отримані дані в автоматизованих процесах.

Зазначена архітектура має низку переваг, основною з яких є забезпечення безпеки, оскільки система функціонує в локальній мережі, що ізолює дані від Інтернет, підвищуючи захист конфіденційної інформації. Використання Anything LLM спирається на централізоване управління системою, що спрощує керування доступом, моніторинг активності та масштабування. Зокрема, можна віддалено перемикатися з однієї LLM на іншу без потреби перезапуску Ollama-серверу.

Розглянута архітектура клієнт-сервер також забезпечує масштабованість системи шляхом додавання нових мовних моделей на сервер Ollama, де кожен клієнт (користувач) має доступ до різних мовних моделей, при цьому всі вони можуть працювати з різними LLM (рис. 2).

Суттєво, що операційна система Windows допускає також можливість запуску кількох різних серверів Ollama одночасно, кожному з яких призначається свій IP-адрес. Це дозволяє розділити користувачів за різними мовними моделями й дещо прискорює роботу кількох з них порівняно з випадком сумісного доступу кількох клієнтів до одного сервера.

Водночас, одним з викликів є необхідність налаштування локальної мережі для забезпечення доступу сервера для клієнтів, що може вимагати певних знань у сфері мережевого адміністрування. Продуктивність системи також залежить від потужності серверу; оскільки у разі недостатності ресурсів, наприклад, GPU, можуть виникати помітні затримки в обробці запитів.

Для успішного впровадження описаної архітектури необхідно провести її тестування з метою оцінки продуктивності системи та виявлення можливих вузьких місць. Зокрема, як з'ясувалося, особливістю Anything LLM є неможливість передачі для аналізу мультимодальній LLM, наприклад, LLaVa [9], зображень, якщо вони попередньо не розміщені у спеціальній базі даних. На рис. 3, 4 продемонстровано етапи підключення ко-

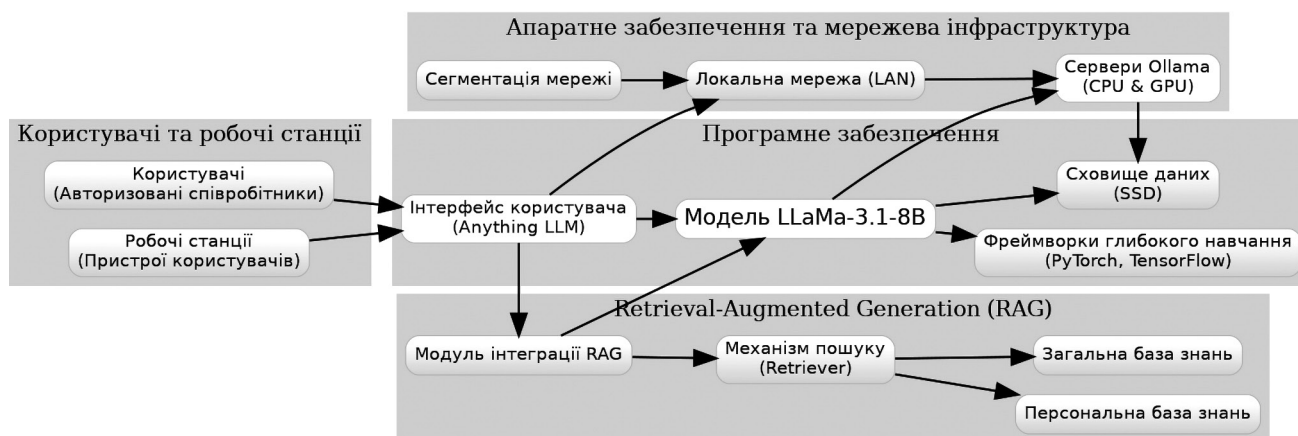
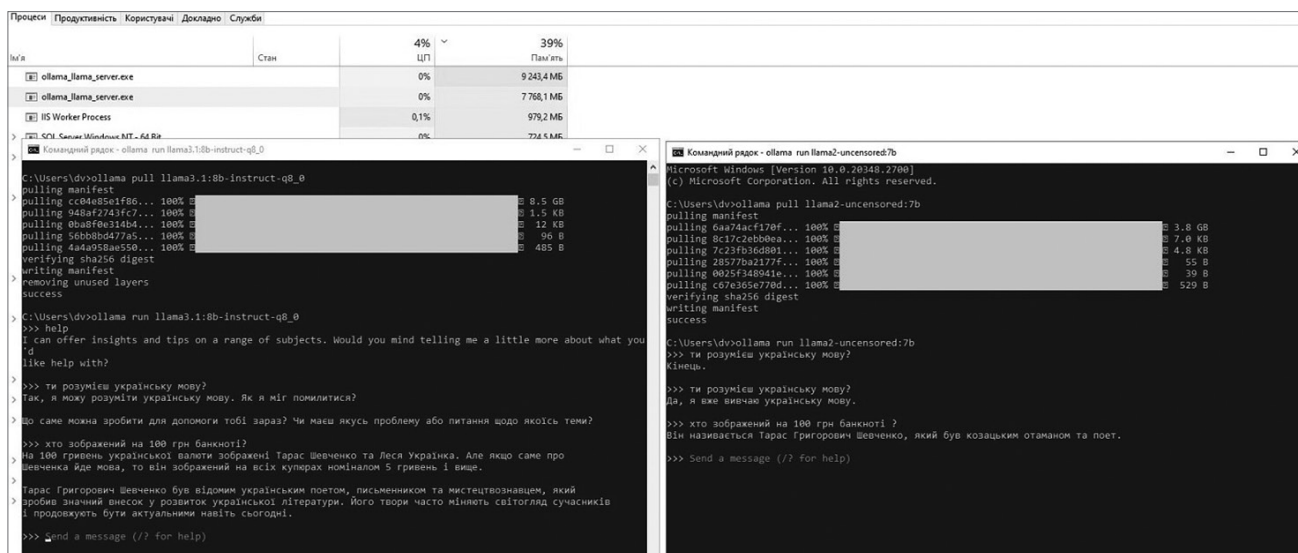
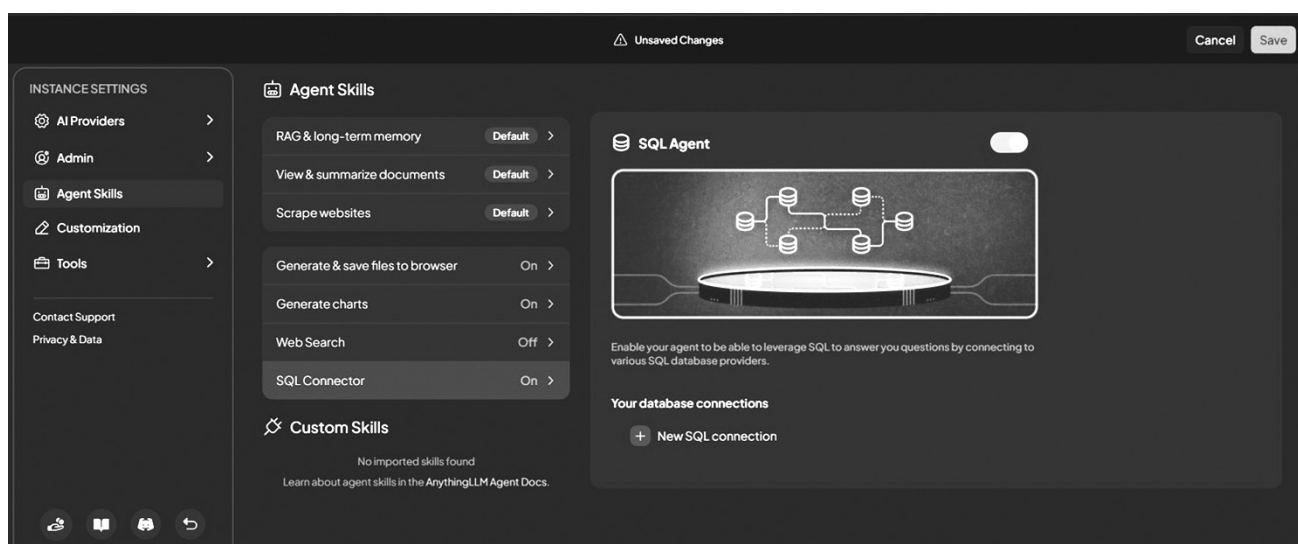


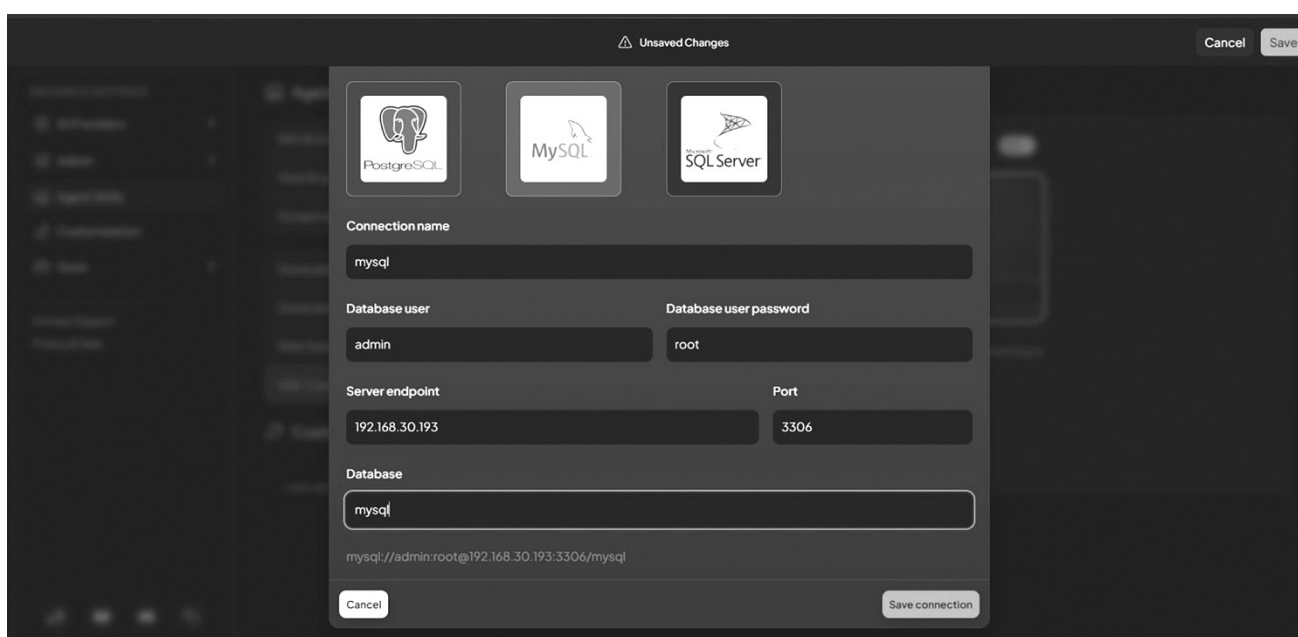
Рис. 1. Типовий варіант розгортання локальної LLM на прикладі українськомовної версії Llama-3.1-8B



Р и с . 2. Демонстрація можливості запуску двох моделей на одному сервері Ollama в операційній системі Windows



Р и с . 3. Підключення системи керування базою даних у налаштуваннях AnythingLLM



Р и с . 4. Вибір системи керування базою даних та підключення до серверу бази даних

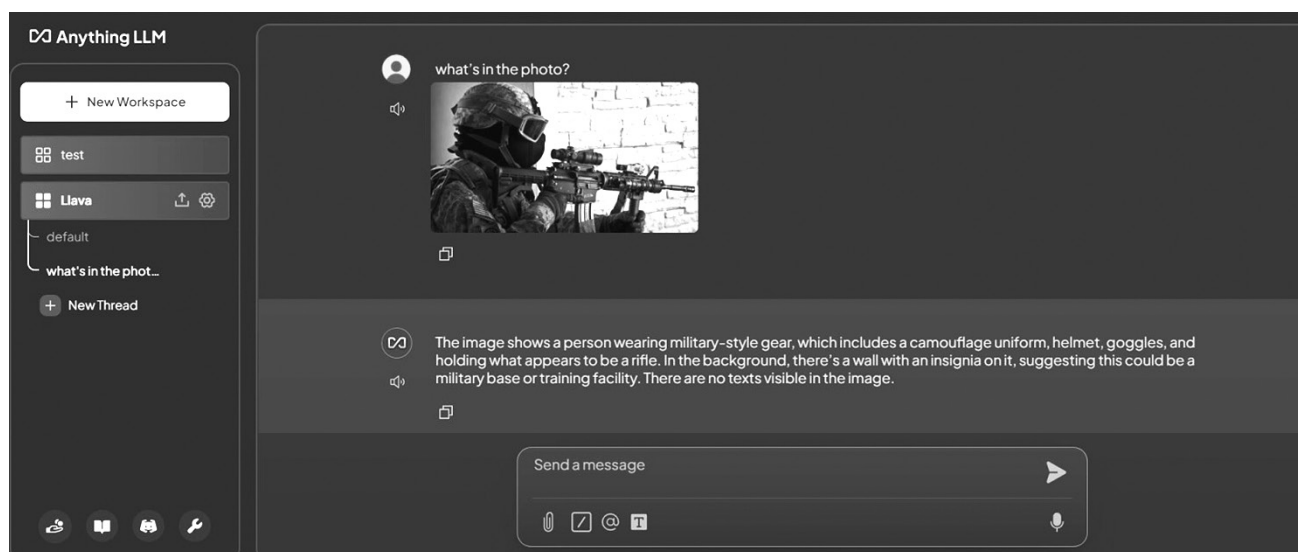
ристувача до серверу такої бази даних і налаштування SQL-клієнта, що інтегрований у середовище Anything LLM, під потреби конкретного завдання. Після проведення підготовчих робіт користувач має можливість надсилати запит до бази даних, використовуючи SQL-клієнта, при цьому важливо правильно налаштувати запит, щоб він відповідав структурі бази даних та забезпечував доступ до потрібного зображення. Після відправлення запиту мультимодальна LLM LLaVa виконує його аналіз і створює опис чи аналізує деталі зображення згідно із завданням користувача. На рис. 5 наведено приклад текстового опису, отриманого після обробки зображення, на якому віддалено розгорнута LLaVa успішно розпізнала об'єкти, сцену та контекст зображення, що дозволяє інтегрувати ці дані в подальший аналіз чи звіти. Такий підхід особливо корисний для завдань, де необхідно автоматизувати процес отримання опису великої кількості зображень, що містяться у спеціалізованих базах даних, датасетах, презентаціях тощо.

В процесі тестування і повсякденного використання необхідно застосовувати систему моніторингу та документування дій для вчасного виявлення проблем і проведення аудиту доступу. Логування процесів функціонування серверу Ollama відбувається в файлах кореневої теки серверу (рис. 6). В ній за допомогою функції

«Viewlogs» можна побачити файли з логами у форматі *.txt, зміст яких відкривається за допомогою стандартного застосунку перегляду текстових файлів (рис. 7).

До основних недоліків описаного підходу можна віднести відсутність детального опису процесу роботи різних мовних моделей на сервері генерації Ollama. Зокрема, досить поверхнева інформація, яка міститься у вказаних логах, не дозволяє оцінити швидкодію конкретних LLM у токенах за секунду, розміри запитів користувачів та обсяги відповідей LLM у токенах. Також до недоліків можна віднести те, що сервер генерації Ollama використовує лише офіційні мовні моделі, які необхідно завантажувати з порталу ollama.com, що ускладнює процес кастомізації мовних моделей на основі технологій тюнінгу [9].

В цілому ж, у військовій сфері запропонована комбінація фреймворків Anything LLM та Ollama може ефективно застосовуватися для обробки розвідувальних даних, автоматизації формування бойових наказів, створення звітів і підтримки прийняття рішень у режимі реального часу [10, 11]. Інтеграція Anything LLM як клієнтського інтерфейсу з можливістю надання доступу через локальну мережу командних пунктів, штабів та установ забезпечить мультимодальний сервіс для командирів й аналітиків, дозволяючи їм оперативно обробляти



Р и с . 5. Результат опису зображення за допомогою LLaVa v.1.5

Ім'я	Дата змінення	Тип	Розмір
server.log	30.09.2024 15:15	Текстовий докум...	241 КБ
app.log	30.09.2024 11:33	Текстовий докум...	1 КБ
app-2.log	30.09.2024 11:09	Текстовий докум...	3 КБ
server-2.log	30.09.2024 11:08	Текстовий докум...	51 КБ
server-4.log	30.09.2024 8:27	Текстовий докум...	43 КБ
app-4.log	27.09.2024 15:45	Текстовий докум...	1 КБ
server-5.log	27.09.2024 15:40	Текстовий докум...	158 КБ
app-5.log	26.09.2024 1:07	Текстовий докум...	2 КБ
upgrade.log	25.09.2024 23:46	Текстовий докум...	253 КБ
config.json	05.08.2024 9:46	Файл JSON	1 КБ
updates	25.09.2024 21:48	Папка файлів	

Р и с . 6. Лог-файли на сервері Ollama



Рис. 7. Відкриті лог-файли роботи серверу та мовних моделей

різноманітну інформацію [12–14] та приймати обґрунтовані рішення. При цьому для підтримки надійності та актуальності системи важливим є регулярне оновлення моделей LLM, фреймворків та систем безпеки для забезпечення стійкої захищеності даних.

АРХІТЕКТУРНІ РІШЕННЯ «КЛІЄНТ-СЕРВЕР» НА ОСНОВІ ФРЕЙМВОРКУ KOBOLDCPP

Іншим можливим варіантом архітектури ізольованої системи з локальною LLM є застосування фреймворку Koboldcpp [15].

Програмне забезпечення Koboldcpp базується на технології llama.cpp і включає API для більшої сумісності та розширених функцій, таких як багатфункціональний користувацький інтерфейс (KoboldCpp Web Application), що підтримує роботу з постійними сценаріями, інструментами редагування, а також різними функціями пам'яті.

В контексті розгортання Koboldcpp у клієнт-серверній архітектурі слід вказати, що серверна частина зазвичай розташовується локально, що дозволяє іншим користувачам у локальній мережі підключатися до неї як клієнтам через вказану точку доступу. Розробники фреймворку Koboldcpp пропонують готові бінарні файли для таких платформ, як Windows, Linux та MacOS, що робить його зручним для використання на різних операційних системах. Запуск Koboldcpp можливий як через графічний інтерфейс, так і через командний рядок, забезпечуючи гнучкість як для початківців, так і для досвідчених користувачів. Така архітектура надає можливість розгорнути сервер на локальному комп'ютері (localhost) і надавати клієнтам у мережі доступ до функцій мовних моделей.

Для прискорення обчислень Koboldcpp підтримує використання GPU, зокрема CUDA для NVIDIA та CLBlast для AMD графічних карт. Крім цього, реалізована можливість перенесення шарів обчислень на GPU, що дозволяє значно прискорити час виконання завдань, хоча для

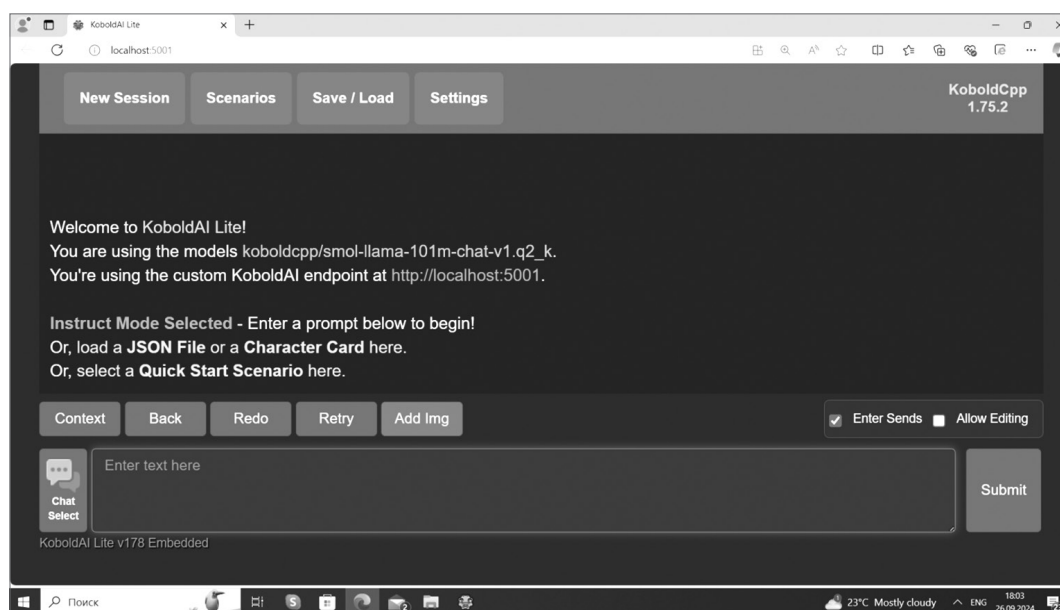
цього потрібно мати більше пам'яті в GPU. Відповідний механізм налаштовується за допомогою команд, таких як '--uselibblas' для CUDA-прискорення, та '--gpuslayers' для вибору кількості шарів, які обробляються на GPU.

У клієнт-серверному режимі серверна частина Koboldcpp запускається із завантаженою мовною моделлю (наприклад, команда 'koboldcpp.py [ggml_model.bin] [port]'). Користувачі або клієнти підключаються до сервера через вказану точку доступу (наприклад, 'http://localhost:5001'), що дозволяє забезпечити інтерактивну взаємодію, як це продемонстровано на представленому на рис. 8 зображенні.

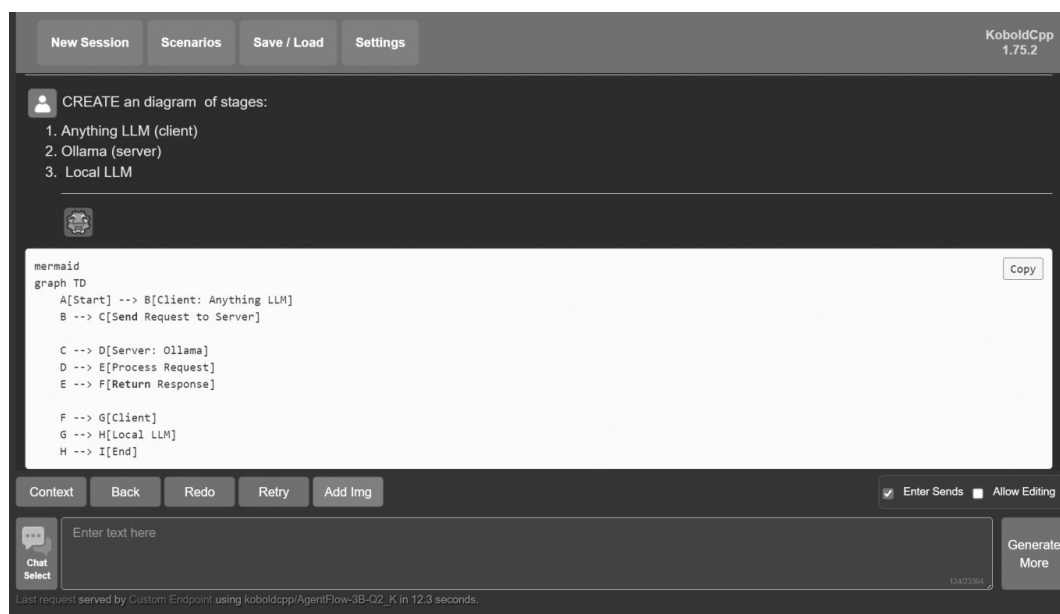
Графічний інтерфейс Koboldcpp підтримує різні режими діалогу, такі як «Instruct Mode», що дозволяє користувачам вводити запити безпосередньо в текстове поле і отримувати відповіді від мовної моделі. При цьому LLM можуть виконувати різні інструкції, подібно до сценаріїв обробки даних, які розглядаються в архітектурі системи локальних LLM [1].

Інтерфейс користувача також містить кнопки «Context», «Back», «Redo», «Retry» та «Add Img» для підтримки інтерактивної роботи, включаючи можливість додавання зображень для розширення контексту. Така функціональність може бути корисною в архітектурі, де клієнти надсилають запити до серверної частини для обробки інформації, зокрема, при використанні мультимодальних моделей, що можуть працювати з текстом та зображеннями.

Інтеграція Koboldcpp до клієнт-серверної архітектури дозволяє виконувати завдання, які були описані в [1], а саме: централізоване управління LLM, забезпечення захисту інформації, а також розширення функціональних можливостей системи для роботи з різними типами даних (текст, зображення тощо). Наприклад, на рис. 9 продемонстровано варіант запуску агентної мовної моделі [16] для описаної в [1] задачі генерації коду діаграми процесів.



Р и с . 8. Графічний інтерфейс Koboldcpp



Р и с . 9. Приклад запуску агентної мовної моделі для генерації коду діаграми процесів

Таким чином, Koboldcpp може бути ефективним інструментом у рамках локальної архітектури для обробки конфіденційної інформації, забезпечуючи можливість використання великих мовних моделей без необхідності підключення до Інтернету. Для детального налаштування фреймворку слід використовувати спеціальні параметри, вибір яких передбачений у меню інтерфейсу Settings (рис. 10). Крім того, для виконання типових завдань доцільно обирати предумовлені типові сценарії (рис. 11).

Розглянемо далі протестовані авторами комбінації Koboldcpp з іншими фреймворками. Це може бути реалізовано як за допомогою браузерного інтерфейсу, так і через спеціалізовані додатки, налаштовані для взаємодії з Anything LLM. Як вже зазначалося, використання таких інструментів, як Anything LLM, спрощує взаємодію користувачів із системою, полегшуючи доступ кількох

робочих станцій до серверної частини з різноманітними функціями, такими як аналіз текстів або інтерактивні бесіди з застосуванням технології RAG.

Комбінація фреймворків, де Anything LLM виступає в ролі інтерфейсу для управління запитам та командами, а Koboldcpp – як обчислювальний бекенд, що альтернативний Ollama, надає можливість створити локальну систему штучного інтелекту з широкими можливостями. При цьому вдається обійти обмеження Ollama щодо придатних до використання мовних моделей. Така система здатна виконувати як базові завдання, так і більш складні інтерактивні сценарії у розподіленій архітектурі, що особливо важливо для захищених середовищ, де чутливі дані не можуть бути передані на зовнішні сервери. Це забезпечує повний контроль над даними та обчисленнями, залишаючи їх всередині захищеної локальної мережі.

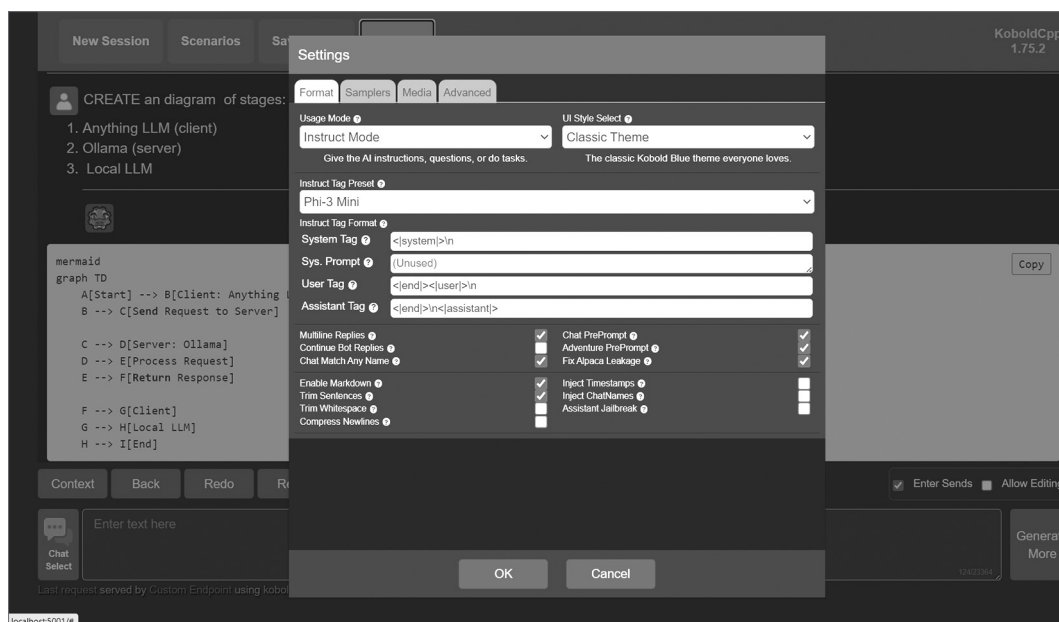


Рис. 10. Детальне налаштування фреймворку Koboldcpp за допомогою спеціальних параметрів у меню інтерфейсу «Settings»

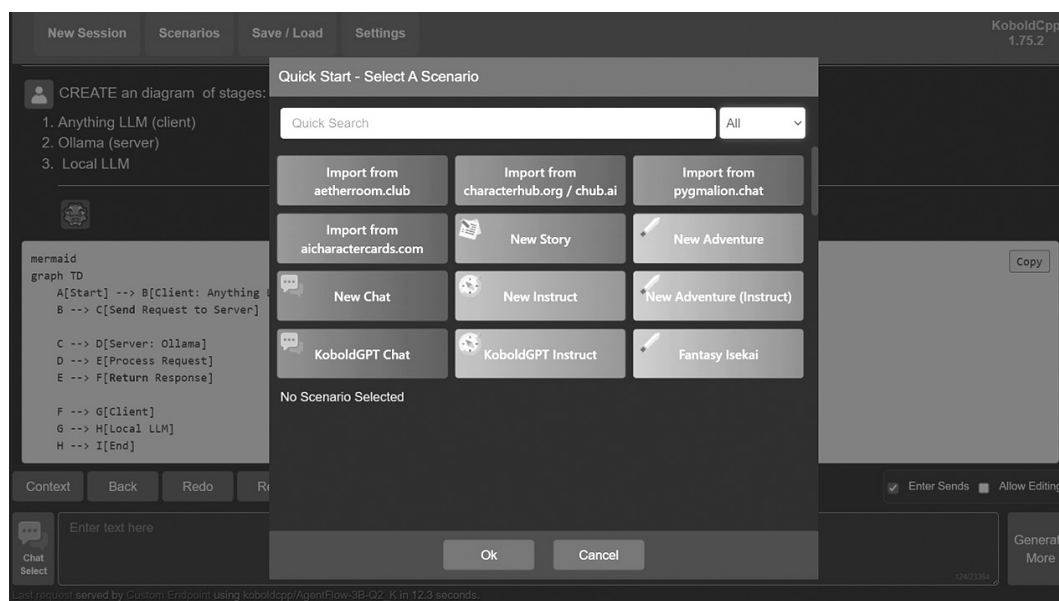


Рис. 11. Меню вибору предустановлених сценаріїв Koboldcpp для виконання типових завдань LLM

ОБМЕЖЕННЯ ФРЕЙМВОРКУ LM STUDIO

Як було вказано в [1], основною перевагою LM Studio виявилось завантаження та використання кастомних (модифікованих або спеціально скомпільованих) мовних моделей під конкретну задачу (рис. 12) та подальше їх локальне використання.

В процесі досліджень авторами було встановлено, що фреймворк LM Studio не може бути використаним в якості серверу з віддаленим доступом та окремим застосунком для підключення до іншого серверу генерації LLM на базі Ollama або Koboldcpp через відсутність функціоналу клієнтської частини.

Причина полягає в тому, що при запуску функції «Сервер» на обчислювальній платформі фреймворк LM Studio рандомно (випадково) призначає IP адресу із доступних мережесх адаптерів, яких на сервері може

налічуватися кілька (рис 13). Відповідно для того, щоб функція сервера запустилася на відповідній IP-адресі, необхідно вимикати всі наявні мережеві підключення окрім адаптера, на якому призначена відповідна IP-адреса, що робить проблематичним віддалений доступ без додаткової конфігурації.

Разом з тим, після проведення необхідної конфігурації та запуску функції сервера, попередньо зазначивши відповідний порт доступу на платформі LM Studio (рис. 14), вдається перевірити працездатність та доступність сервера генерації на локальній абонентській станції за допомогою функції «GET» через веб-застосунок і отримати назву мовної моделі, яка завантажена та використовується платформою LM Studio (рис. 15).

Переконавшись в ініціалізації мовної моделі в LM Studio, можна спробувати здійснити підключення клі-

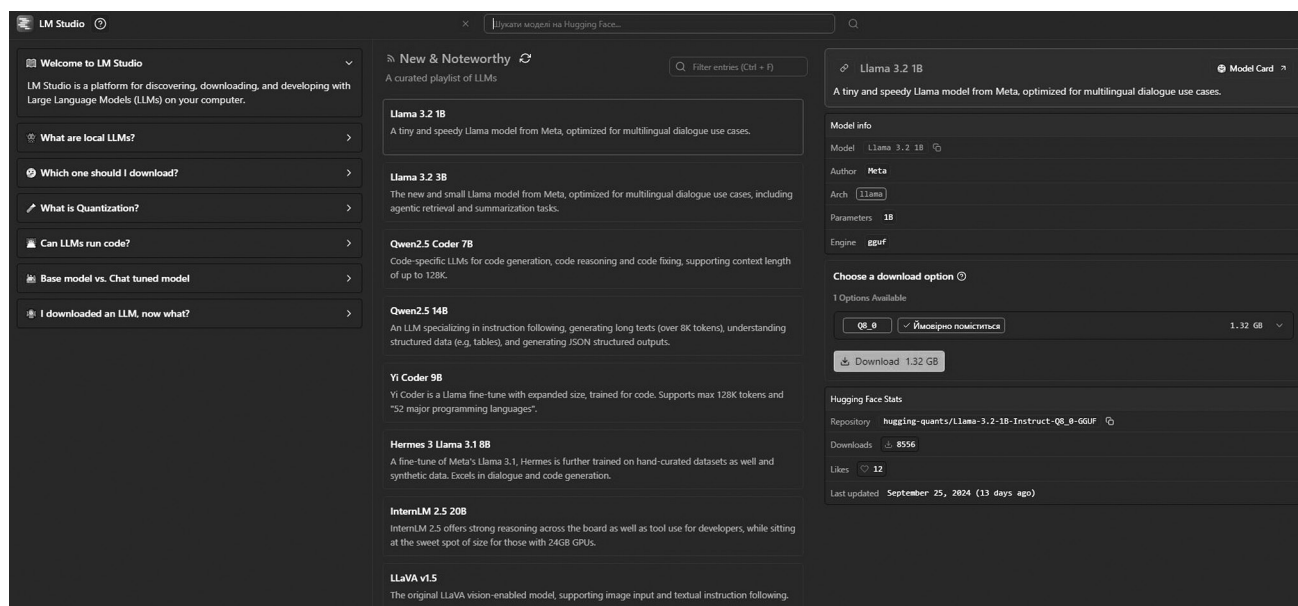


Рис. 12. Основне меню завантаження мовних моделей

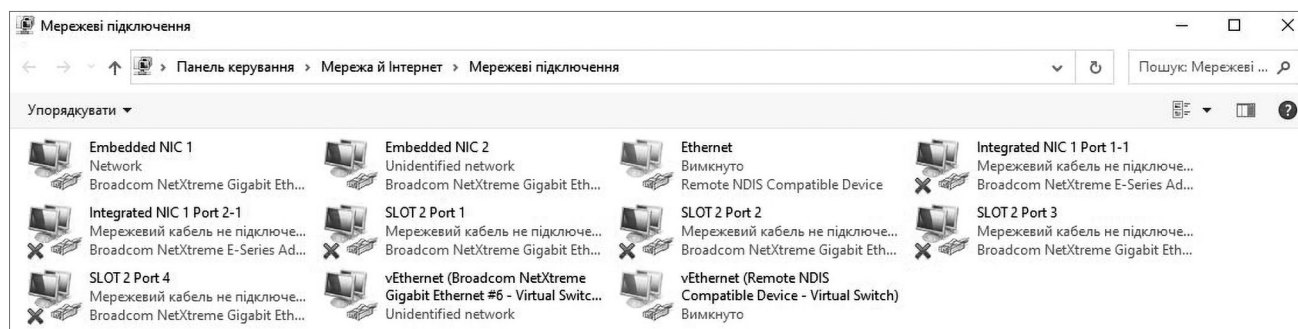


Рис. 13. Приклад наявних мережевих адаптерів на сервері

ентської частини AnythingLLM до серверу генерації LM Studio (рис. 16), зазначивши IP-адресу та порт доступу до сервера. В результаті модель, яка завантажена на сервері генерації, автоматично підключається на клієнтській частині.

Після вибору мовної моделі необхідно здійснити налаштування робочого простору AnythingLLM (рис. 17) та переконатися, що бажана LLM підключена у відповідному чаті. Однак успішне виконання описаних операцій не дозволило забезпечити досягнення головної мети дослідження, що полягала у реалізації чату з LLM, оскільки тестова відправка повідомлення у чаті призводить до виникнення помилки (рис. 18).

В логах на серверній частині (рис. 19) теж фіксується помилка «Only user and assistant roles are supported», що означає, що дана модель може використовуватися лише з ролями «користувач» та «асистент». В даному випадку локальний клієнт сервісу має роль «користувача», а сервер – «асистента».

Відповідно, при запиті клієнтської частини AnythingLLM до серверу генерації LM Studio виконується компіляція з параметрами «role – system» та «role – user», що не припустимо для подальшої генерації відповіді на запит у зв'язку з некоректним параметром «System». Відповідно до технічної документації, зазначеної на офіційному сайті LM Studio та на платформі репозиторіїв

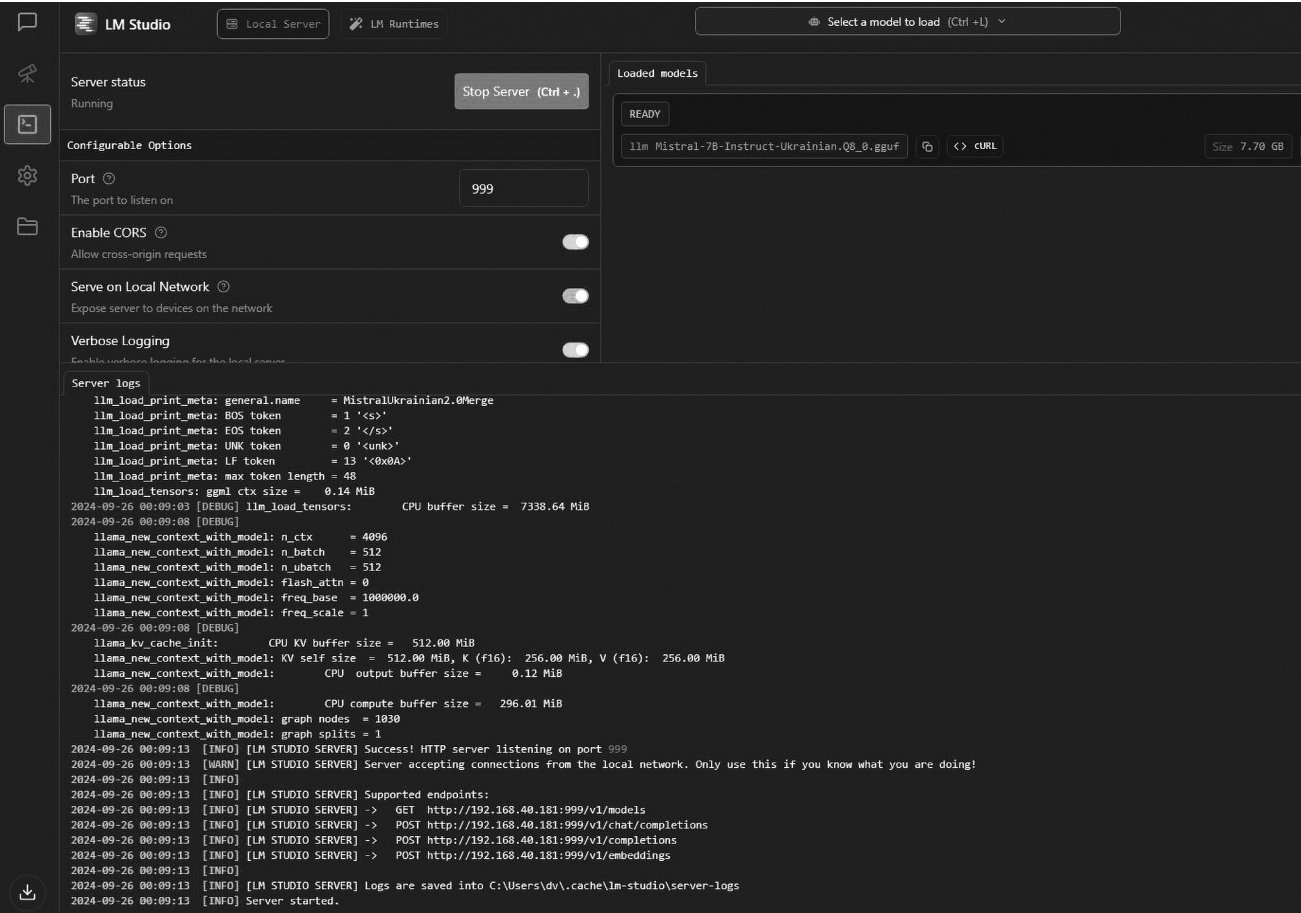
GitHub, визначення даної помилки на момент написання статті не фіксувалося.

Також було виявлено неспроможність роботи з LM Studio в якості віддаленого клієнта у комбінації з серверами на базі інших фреймворків. Це означає, що найефективнішим варіантом використання LM Studio залишається розгортання локальної LLM на одному й тому ж комп'ютері з LM Studio [1].

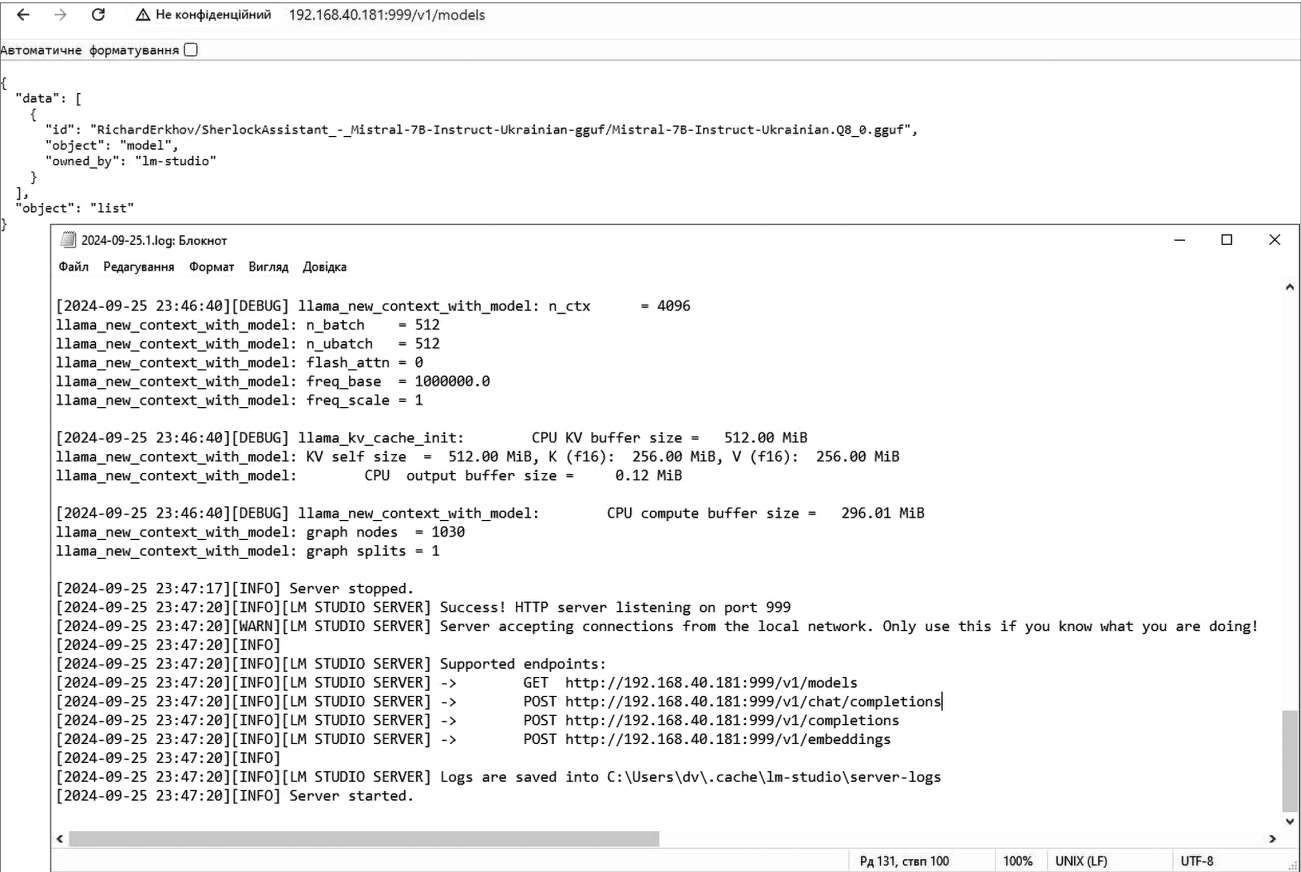
Вказані висновки були підтверджені на основі аналізу доступних матеріалів Інтернет-форумів та документації LM Studio [17].

Інтеграція LM Studio з іншими сервісами на основі REST API також ускладнена, оскільки API LM Studio не має необхідних можливостей для легкого контролю доступу. Ситуація може змінитися у майбутньому, якщо розробники запровадять підтримку повноцінного API або SDK для Python, що дозволить ефективніше інтегрувати LM Studio з іншими системами [18].

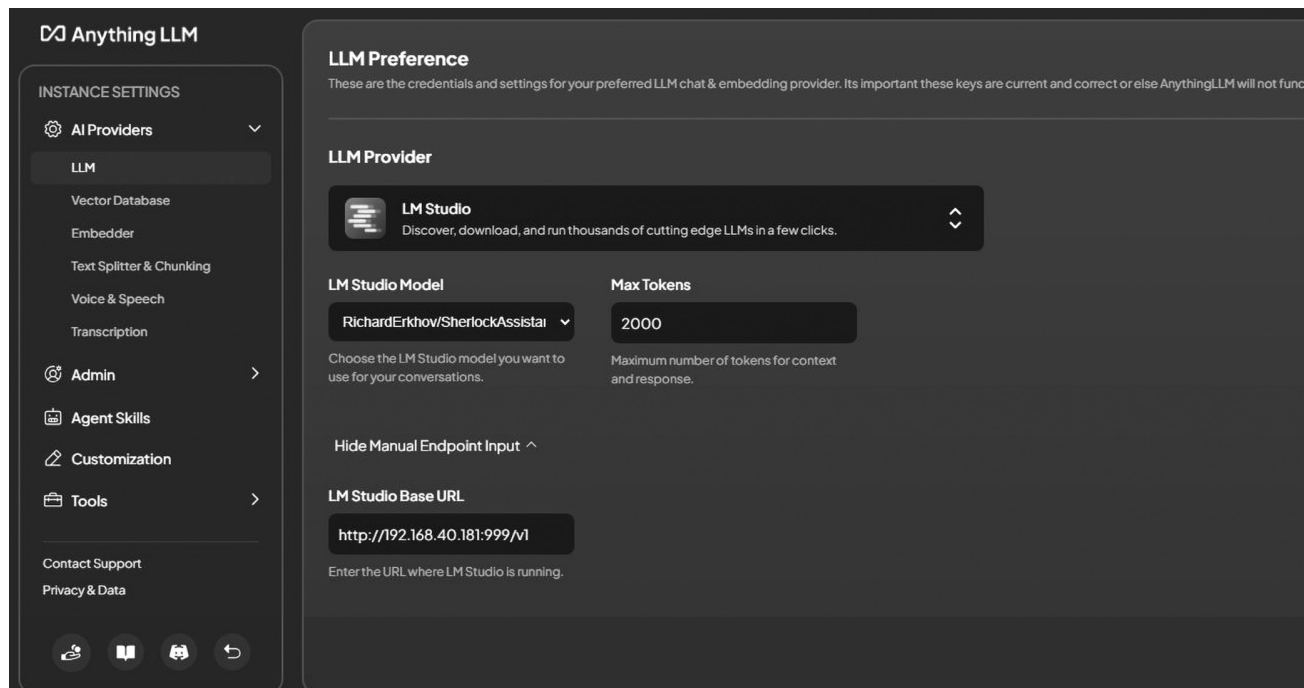
В якості висновку слід зазначити, що залежно від вирішуваного завдання на даному етапі розвитку технологій LLM кращим вибором серед розглянутих варіантів їх локального розгортання є застосування в якості серверних платформ фреймворків Ollama або Koboldcpp. У разі потреби у використанні додатково налаштованих за допомогою тюнінга мовних моделей Koboldcpp лишається єдиним серверним рішенням.



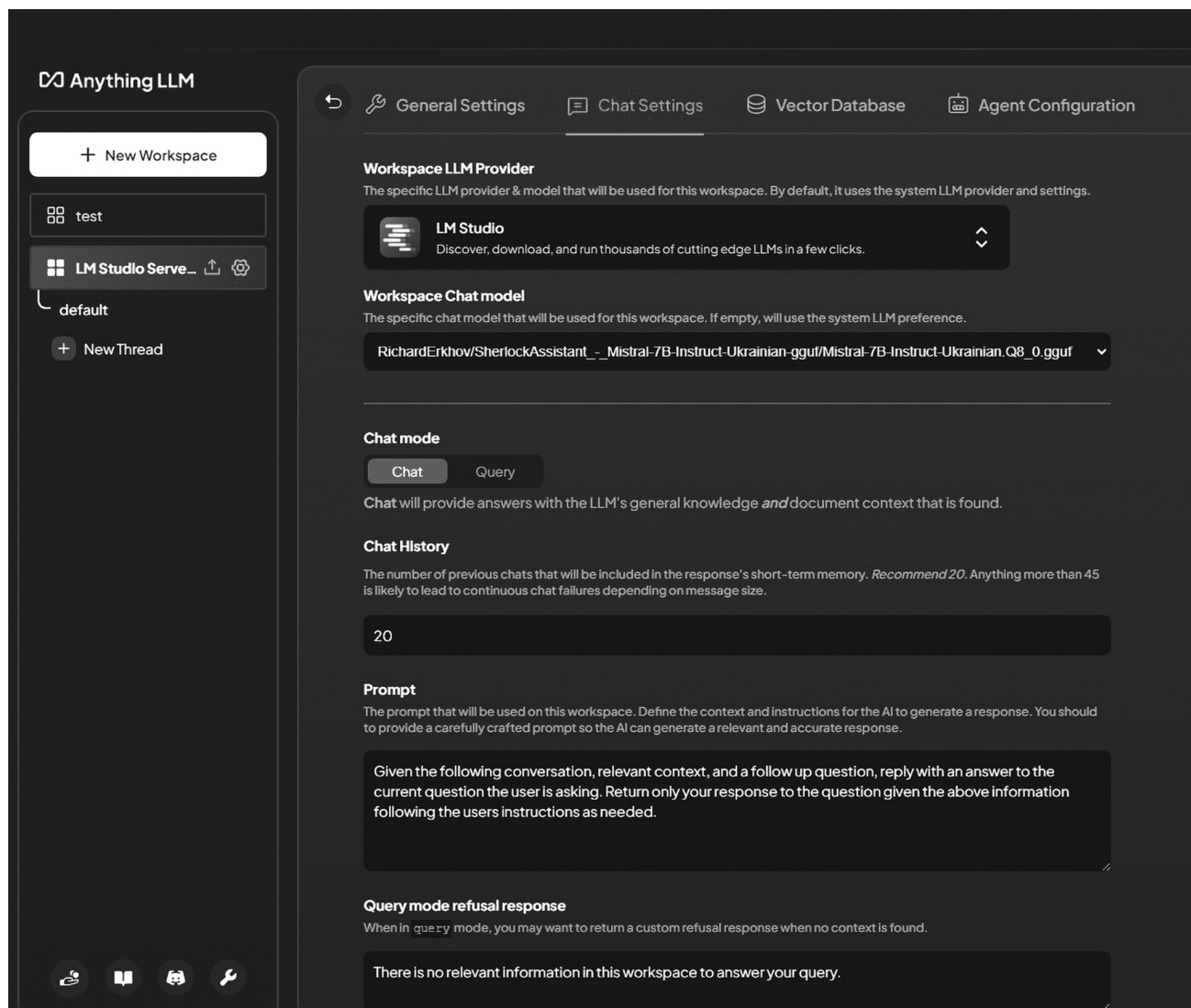
Р и с . 14. Запуск функції Сервер на платформі LM Studio



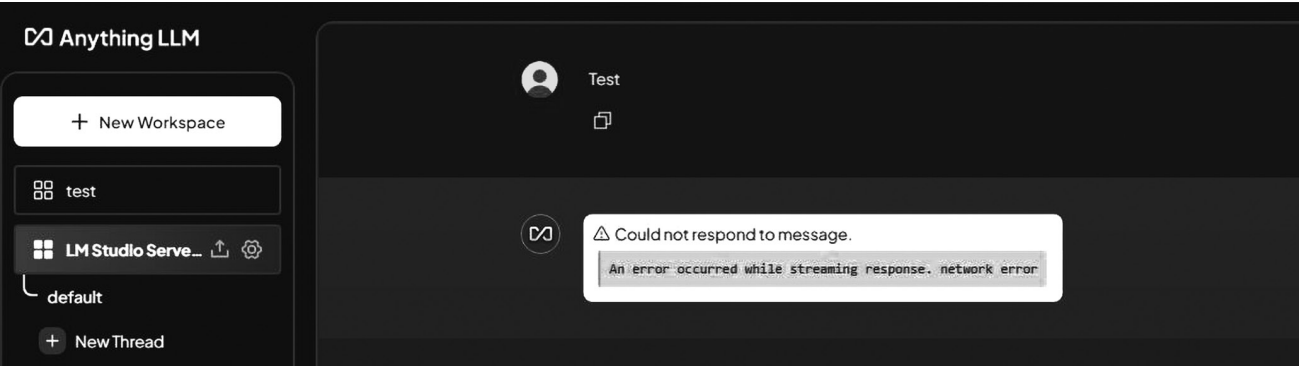
Р и с . 15. Результат перевірки доступу до серверної частини LM Studio



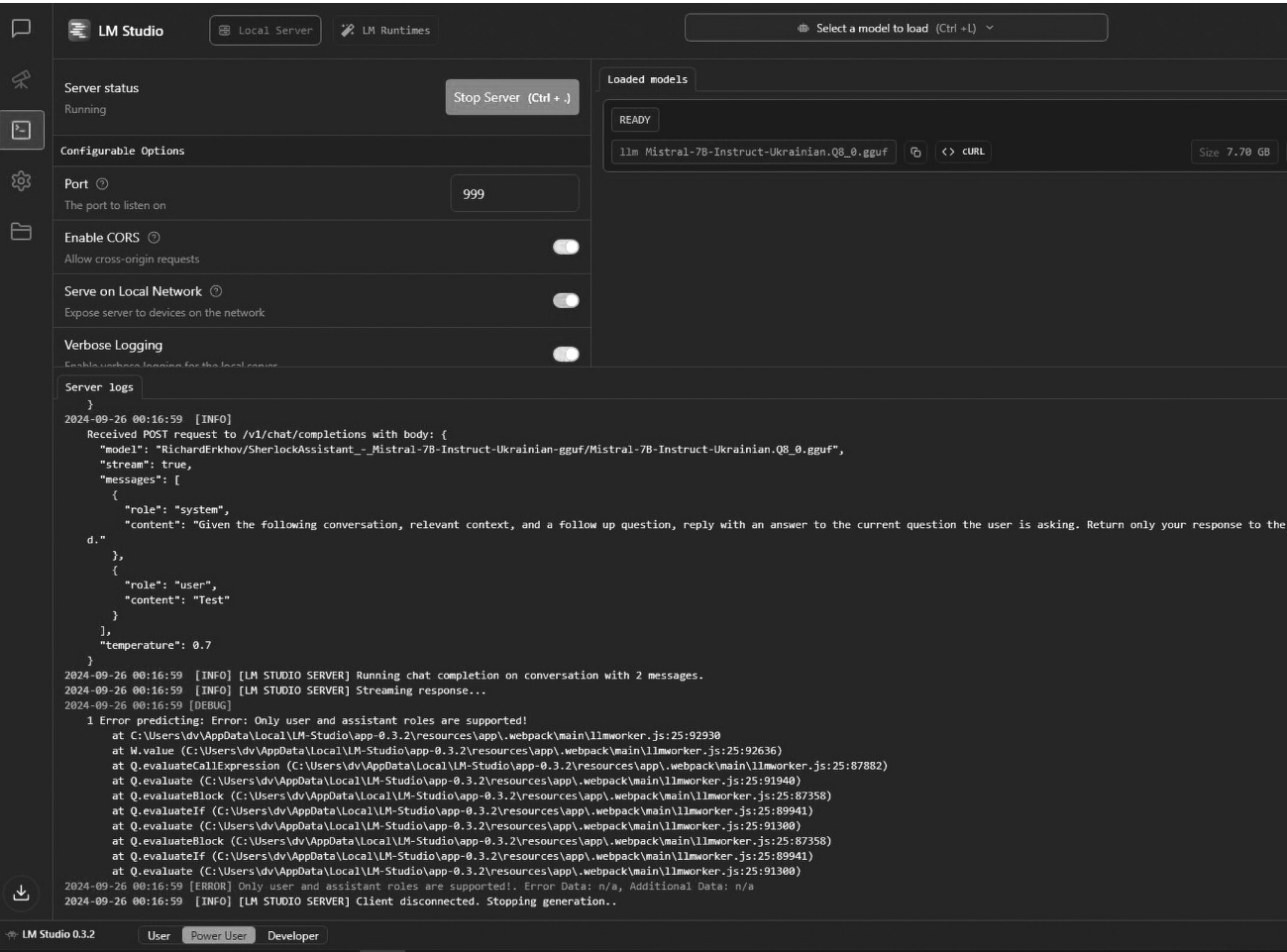
Р и с . 16. Налаштування клієнтської частини AnythingLLM



Р и с . 17. Налаштування робочого простору AnythingLLM



Р и с . 18. Результат виконання запиту «Test»



Р и с . 19. Лог виконання запиту «Test»

При цьому для підтримки локальних баз даних з конфіденційною інформацією на основі механізму RAG слід обирати комбінацію в якості клієнтського програмного застосунку Anything LLM, а сервера – Koboldcpp. Такий підхід дозволить зекономити кошти шляхом відмови від розробки власного або застосування пропріетарного програмного забезпечення і створить передумови для впровадження технологій штучного інтелекту у повсякденну військову та наукову діяльність у короткі строки.

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PRACTICAL ASPECTS OF DEPLOYING LARGE LANGUAGE MODELS IN LOCAL NETWORKS

The article examines practical aspects of deploying large language models (LLMs) in local networks for processing confidential information. The authors analyze the capabilities of frameworks such as LM Studio, Ollama, Anything LLM and Koboldcpp within different client-server architecture scenarios. Particular attention is paid to functional limitations, technical nuances of configuration, as well as the efficiency and security of utilizing these systems to address tasks in military and scientific domains. Specifically, the article describes a combination of Anything LLM and Ollama frameworks, which ensures integration with knowledge bases through the Retrieval-Augmented Generation (RAG) mechanism, enabling secure data processing in a local environment.

The advantages of architecture based on the Koboldcpp framework, which supports model customization and integration with GPUs to accelerate computations, are detailed. Challenges associated with using LM Studio to create a server infrastructure are also explored, particularly due to its limited API functionality and the complexity of access configuration. The article emphasizes that the optimal choice for locally deploying LLMs in a client-server architecture is the combination of Anything LLM as a user interface and Koboldcpp as a server platform. This system provides flexibility, resource efficiency and high data security, which is particularly critical for applications in the field of national security.

Additionally, the article highlights the importance of testing and configuring the chosen frameworks to ensure system reliability, scalability and compatibility with various user scenarios. The potential use of such architectures for tasks such as real-time intelligence analysis, automation of operational commands and reporting processes in military contexts is also discussed. These solutions are presented as practical and cost-effective approaches to rapidly integrate artificial intelligence technologies into everyday military and scientific activities.

Keywords: local large language models, confidential information processing, client-server architecture, LLM fra-

meworks, local network, Retrieval-Augmented Generation, data security, server configuration.

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FORMATION OF POSSIBLE SCENARIOS FOR THE DEVELOPMENT OF ABNORMAL SITUATIONS DURING TESTS OF CONTROLLED MEANS OF DESTRUCTION

The article presents a methodological approach to the formation and development of possible scenarios for the development of emergency situations during the testing of guided weapons by describing their structure and functioning based on logical-probabilistic theory. In this case, the structure of the object under study is described by a function of the algebra of logic, and the quantitative assessment of the operational state is described by a probabilistic function, which allowed the application of the basic theorems of probability theory.

Possible scenarios for the development of emergency situations when using guided weapons were considered provided that their occurrence is due to the failure of one or more components or a violation of the connections between them. As an example of the development of an emergency situation, a possible scenario for the transition to unguided flight of an air-to-air guided missile is given.

Keywords: *probabilistic function, guided weapons, emergency situation, operational state, component, complex technical system, function of the algebra of logic.*

INTRODUCTION

Modern guided weapons (GW) consist of a large number of systems, blocks, assemblies, parts, etc. (component parts), each of which performs its functions, is built on the use of certain physical principles and has connections with other component parts. Their main features are relative independence (connection with the launch platform is lost after launch) and the possibility of only one-time use for its intended purpose. Although the structure of the GW is determined by the combat purpose, they all have common features in the organization of construction and equipment composition – that is, they are typical representatives of complex technical systems (CTS) and can be considered from the perspective of the theory of complex systems in both organizational and functional aspects [1].

Reliability is usually used as an integral indicator of the operational properties of CTS, that is, the ability of the system to maintain its properties and function as intended under certain conditions and for a certain time [2].

Thus, the operational state of the GW, as CTS, is characterized by the ability to perform its functions as intended and is determined by the technical condition of the medium and the connections between them. Loss of operability of one or more medium or violation of connections between them leads to failure of the GW as a whole [2]. When used as intended, the consequence of such an event may be the occurrence of emergency (abnormal) situations (ES) and failure to complete the task.

Thus, the operational state of the GW, as CTS, is characterized by the ability to perform its functions as intended and is determined by the technical condition of the components and the connections between them. Loss of operational capacity of one or more components or a violation of the connections between them leads to the failure of the GW as a whole [2]. When used as intended, the consequence of such an event may be the occurrence of emergency situations (ES) and failure to complete the task. Emergency situations also include situations that are caused by deviations from normal (standard) conditions of use. Their possible consequences are necessarily analyzed when assessing risks, building scenarios for the occurrence and development of accidents, catastrophes, etc. It is obvious that the more complex the system, the more medium-frequency components it contains, the more complex the connections, the more complicated the process of analyzing and predicting its state, and the greater the potential danger it carries.

The basic principles of assessing the reliability and safety of the functioning of the CTS have many common features and, from a mathematical point of view, can be carried out using identical mathematical tools and create the prerequisites for the formation of possible scenarios for the development of emergency situations, identifying the cause and developing measures to prevent or minimize their consequences.

The purpose of the article is to develop a methodological approach to the formation of possible scenarios for the

development of emergency situations in the functioning of the GW when conducting tests using logical-probabilistic methods.

RESEARCH RESULTS

The issues of formation and development of possible scenarios of development of emergency situations during testing, along with the theory of reliability, aging are increasingly found in works [3–10], in which they are solved from the position of the theory of STS and the basic provisions of the algebra of logic are applied. At the same time, the means of mathematical logic are used to analyze the structure of STS and ways to increase their reliability are developed on the basis of quantitative assessments of reliability using the theory of probability. Such approaches allow solving the general tasks of creating reliably functioning systems taking into account negative factors, the target function of which is to ensure a working condition in various operating conditions.

At the same time, testing of samples of GW, which is associated with launching (firing), carries risks of abnormal and emergency situations [11, 12]. In most available sources, insufficient attention was paid to the issue of the occurrence and development of abnormal situations during testing of weapons and the features of their construction and functioning as single-use CTS were practically not considered.

The formation of a list of possible failure variants of components and related emergencies is carried out based on the results of a schematic analysis of the design of the GW sample and functional-morphological decomposition with preference for the functional feature, the result of which is the distribution of the causes of malfunctions and damage that lead to the emergence of an emergency situation into groups [13]. The general algorithm for the development and formation of possible emergencies is shown in Fig. 1. It should be noted that the most common is the transition of the GW to uncontrolled flight.

According to the results of decomposition, several hierarchical levels are distinguished, determined by different degrees of abstraction regarding the technical, physical, chemical and other properties of the components and an ordered hierarchical set is formed, which can be represented in the form of a single-root hierarchical graph, table, structured diagram, etc. This allows us to consider the GW as a CTS consisting of separate interconnected systems, which, in turn, can also be divided into subsystems, units, blocks, etc.

To assess the operational state of the GW, we will use the logical-probabilistic method, the essence of which is that their structure is described by the function of the algebra of logic (FAL) [5, 6] and the quantitative assessment of the operational state is carried out by the methods of reliability theory and mathematical statistics [13].

As is known, FAL is formed from statements (random events) that are connected by logical operations (conjunction, disjunction, negation, equivalence, etc.). In this case, statements can take only two values: 0 (false) or 1 (true). In most cases, CTS are described by FAL with repeated arguments or negation arguments, which does not allow direct

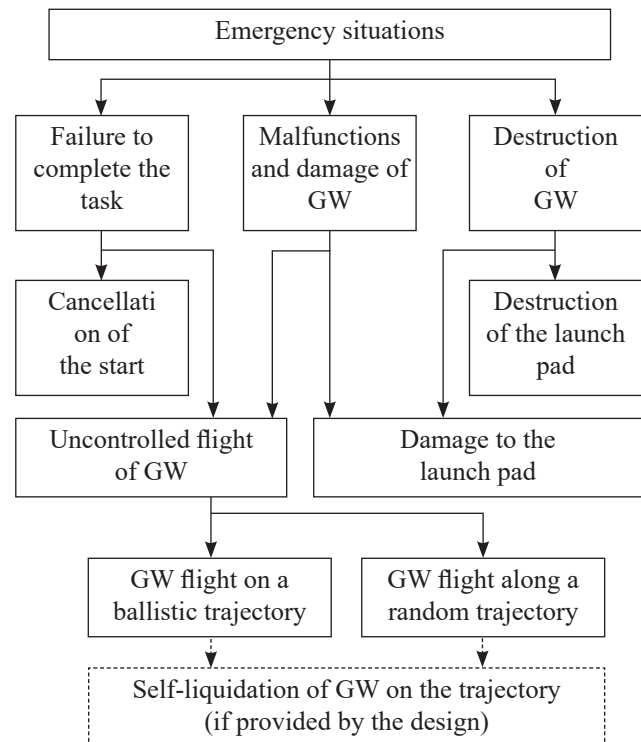


Fig. 1. Algorithm for the development and formation of possible emergency situations

use of known methods of reliability theory. To transition from FAL to a probabilistic function (PF), it is necessary to replace the logical variables of the function with the probabilities of failure-free operation and the logical operations with arithmetic ones. As a result of the transformation, the PF will act as the probability of the truth of FAL.

Thus, using FAL, it is possible to describe the conditions of the GW's operability, which will allow us to identify such components and their connections, due to which a failure (loss of operability) may occur, which will lead to an emergency situation. Taking into account the above, we will describe the FAL of the operability of the GW in the form of a structure that can be in two states – operable ($y = 1$) or inoperable ($y = 0$). In this case, the state of the system (y) depends on the state of its components (x_i), which can also be in operable ($y = 1$) or inoperable ($y = 0$) states. The values $x_1, x_2, \dots, x_i, \dots, x_m$ of binary variables and determine the GW state vector as a whole. Therefore, in the general case, the FAL of the operability of the GW can be written as

$$y(x_1, x_2, \dots, x_i, \dots, x_m) = y(X). \quad (1)$$

The procedure for assessing the operational state of GW using logical-probabilistic theory approaches is shown in Fig. 2.

In principle, there are two approaches to analyzing possible scenarios for the development of emergency situations [6].

The first approach consists in analyzing the development of events, starting from the moment of the emergency situation and until the detection of failures of those components that will lead the GW to an inoperable state, that is, the analysis of the accident is carried out «from the end to the beginning». In this case, the reasons (events, a

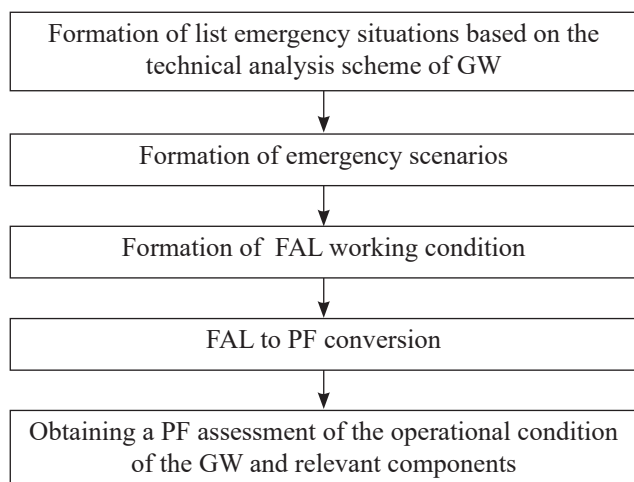


Fig. 2. Procedure for assessing the operational condition of the GW

combination of several events) that lead it to such a state are analyzed. In the process of analysis, a logical scheme is also built, which contains all possible combinations of events. A logical function is built based on the logical scheme, the arguments of which are the primary events.

The second approach involves analyzing the development of events in the reverse direction – from the moment of failure of a component to the beginning of the development of an emergency situation. After the initial failure is determined, a scenario of its development within the system is formed based on the existing connections between the components. Thus, the system's reaction to the failure that

has occurred is determined. The second approach also solves the problem of finding ways for the system to transition to an inoperative state under the condition of any initiating event, that is, it represents an analysis of the accident «from beginning to end».

It should be noted that the formation of emergency scenarios occurs in chronological order, even when events occur with a small difference in time.

After completing the analysis using one of the above approaches, a logical diagram is built that contains all possible scenarios for the development of emergency situations and allows you to graphically display the logic of failures in the GW. According to this diagram, a logical function is built, the arguments of which are the events present in the scenario. In some cases, it is necessary to take into account the possibility of operation of individual subsystems in the situation that develops before their regular connection.

As a rule, it is convenient to present FAL in disjunctive normal form (DNF), with each conjunction representing the path of the loss of performance, i. e. the scenario of the development of an emergency situation. As an example, Fig. 3 shows scenarios of the development of emergency situations, which leads to the transition to unguided flight of an aircraft guided missile of the «air-to-air» class of short/medium range. In this case, the «from beginning to end» approach was used. In this case, expression (1) will have the form

$$y = z_{13} \vee z_{14} \vee z_{15}.$$

To assess the probability of occurrence of emergency scenarios, we will move from FAL to PF, as which we

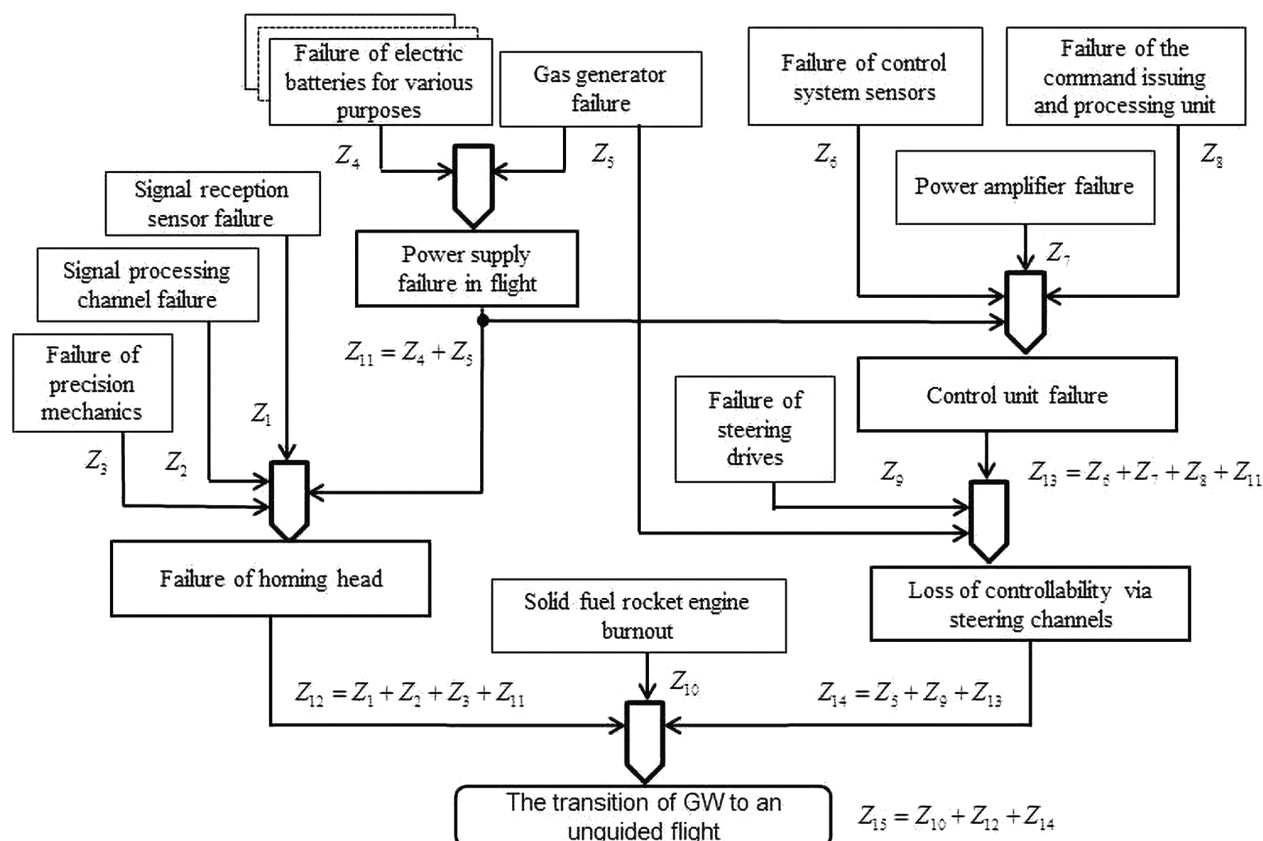


Fig. 3. Possible scenarios for the development of an emergency situation – the transition of an aircraft guided missile into uncontrolled flight

will use the probability of failure-free operation, which will allow us to apply the basic theorems of probability theory. For the analysis of sequential, parallel and tree-like structures, the formula of total probability can be used.

After constructing possible scenarios of the development of emergency situations (construction of FAL), the probability of their implementation is estimated. Next, the impact of each component on the development of each of the possible scenarios is assessed by translating FAL into PF, the arguments of which are the corresponding probabilities of failure-free operation included in the logical schemes. The probabilities of failure-free operation of the components included in the studied GW are determined by expert methods taking into account the construction of their structural and functional reliability schemes [1], according to design and technical documentation, relevant characteristics of similar products, etc. At the end, by substituting the corresponding probabilities in PF, the probability of the final event is calculated.

For example, the FAL of the transition to uncontrolled flight of an aircraft guided missile (Fig. 3) as a result of the failure of the homing head has the form

$$y_{hh} = z_1 \vee z_2 \vee z_3 \vee z_{11},$$

that is, its normal operation depends on the technical condition of the signal reception sensor, signal processing channel, precision mechanics and power supply, and the probability of its trouble-free operation is calculated as

$$P_{hh} = P_{SRS} \cdot P_{SPC} \cdot P_{PM} \cdot P_{PS},$$

wherein P_{SRS} , P_{SPC} , P_{PM} and P_{PS} – the probability of failure-free operation of the signal reception sensor, signal processing channel, precision mechanics, and power supply, respectively.

It is obvious that the probability of a guided missile going into uncontrolled flight due to a homing head failure and the occurrence of a corresponding emergency situation is equal to

$$P_{UF\ hh} = (1 - P_{hh}).$$

In a similar way, it is possible to calculate the probability of a rocket going into uncontrolled flight caused by failures of the control unit, gas generator, burnout of a solid fuel engine in flight, etc.

For organizational and technical systems and high-dimensional CTS, well-known methods of FAL and PF conversion are used, of which the most convenient for practical application are the orthogonalization method, the recurrent method and the path-building method [6]. The most complex of them from the point of view of calculation is the orthogonalization algorithm, which is based on the conversion of FAL into orthogonal DNF. It is proposed to be used in the case when the probabilities of events have approximate values, since the total calculation error will be smaller due to the fact that the probabilities are added when performing the conversion.

The recurrent algorithm is based on calculations using the tabular method using the multiplication theorem of event probabilities. In these tables, the columns are the number

of possible combinations of conjunctions and the rows are the number of elements in the system. This algorithm is the least computationally cumbersome due to the lack of the need for additional function transformations and is most efficient if the number of DNF members does not exceed 10. In the path building algorithm, the relative probability of impossibility of all previous paths is used when calculating the probability, i. e. some variables are replaced by 1, which significantly simplifies further calculations.

To make a decision on the adoption of GW of domestic and foreign production into service (admission to operation), it is usually necessary to confirm their individual tactical and technical characteristics. The results of such tests can also be used to refine the algorithm for the combat use of GW. In this case, appropriate flight tests are carried out at the training grounds of the Armed Forces of Ukraine, which requires the calculation of the danger zone, the geometric dimensions of which are determined by the set of possible variants of their abnormal operation.

The analysis of the possible behavior of the GW both in normal flight and in the event of one or more failures is carried out based on the results of the study of the corresponding mathematical model, which is based on the known equations of motion of the center of mass and motion around the center of mass. The adequacy of this model and its accuracy are confirmed by the corresponding flight tests. At the same time, a search is made for such combinations of possible failures, at which they take maximum values. The far boundary of the danger zone is determined by the energy-ballistic characteristics of the GW and the near boundary corresponds to the flight range at the maximum deflection of the aerodynamic rudders, as well as a possible engine burnout, which can cause a significant transverse thrust moment. The lateral boundaries of the danger zone are determined by the ballistic flight range at the corresponding deflection of the aerodynamic rudders and also a possible engine burnout. The total danger zone is formed by combining all partial zones, with reference to the start point and direction to the target.

As an example, Fig. 4 shows partial and total danger zones, which were calculated by the State Enterprise State Kyiv Design Bureau «LUCH» when organizing the testing of one of the GW types. Based on the results of mathematical modeling, trajectories, speeds, coordinates of the impact points and other parameters used to determine them were calculated. The set of impact points (taking into account the radius of the fragmentation) form partial danger zones caused by the corresponding emergency situations (ES1 – ES7).

CONCLUSIONS

It is proposed to form a list of possible GW emergency situations based on the results of functional-morphological decomposition with preference given to the functional feature, the result of which is the distribution of causes of malfunctions and damage that lead to emergency situations into groups. To assess the operational state of the GW sample, a logical-probabilistic method is used, with its structure described by a function of logic algebra and the operational state by methods of reliability theory. After the

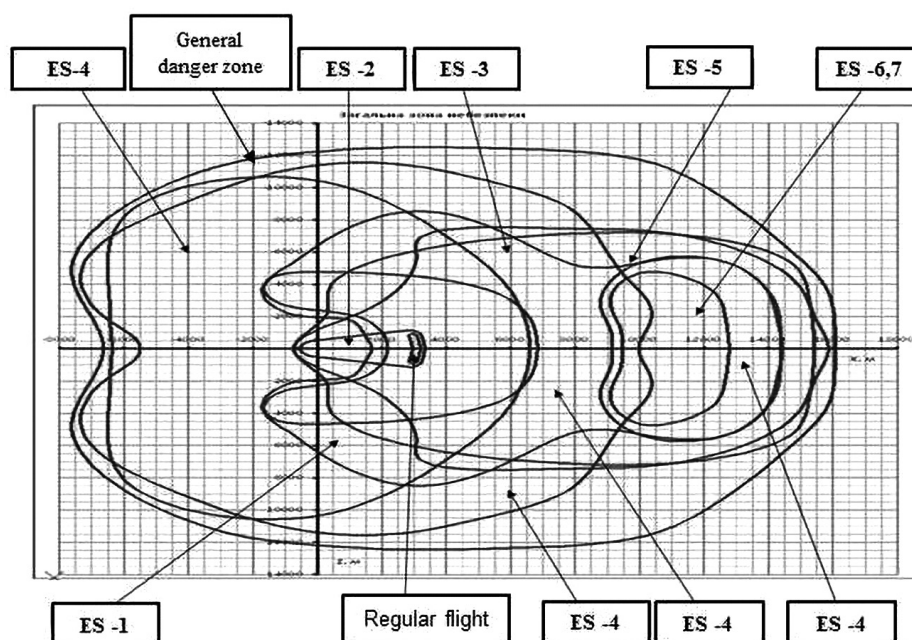


Fig. 4. Partial and total danger zone calculated for GW tests

analysis is completed, a logical diagram is constructed that contains all possible scenarios of emergency situations and allows graphically displaying the logic of failure occurrence. A logical function is also constructed using this diagram, the arguments of which are the events present in the scenario.

The presented methodological approach to the formation of possible scenarios of the development of emergency situations during GW tests allows us to assess the probability of their occurrence and the obtained PF of failure-free operation and the corresponding assessment of their elements allow us to identify a list of events and components whose impact on operability is the greatest. Their significance and role in possible scenarios of the development of emergency situations should be used when developing and calculating danger zones during flight tests of weapons of various purposes. The results of such tests can also be used to refine the algorithm of combat use.

The proposed methodological approach was used by specialists of the State Enterprise State Kyiv Design Bureau «LUCH» to calculate danger zones when organizing control flight tests of a number of KZU of foreign production and of our own development and production.

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ФОРМУВАННЯ МОЖЛИВИХ СЦЕНАРІЇВ РОЗВИТКУ НЕШТАТНИХ СИТУАЦІЙ ПРИ ПРОВЕДЕННІ ВИПРОБУВАНЬ КЕРОВАНИХ ЗАСОБІВ УРАЖЕННЯ

У статті наведено методичний підхід щодо формування та розвитку можливих сценаріїв розвитку нештатних ситуацій при проведенні випробувань керованих засобів ураження шляхом описання їх структури та функціонування на основі логіко-ймовірнісної теорії.

Для оцінки працездатного стану керованого засобу ураження застосовується логіко-ймовірнісний метод, при цьому його структура описується функцією алгебри логіки, а працездатний стан – методами теорії надійності. Після завершення аналізу будується логічна схема, яка містить усі можливі сценарії розвитку нештатної ситуації та дозволяє графічно відобразити логіку виникнення відмов. За цією схемою також будується логічна функція, аргументами якої є події, що присутні в сценарії.

Можливі сценарії розвитку нештатних ситуацій при застосуванні керованих засобів ураження розглядались за умови, що їх виникнення обумовлено відмовою однієї чи декількох складових частин або порушенням зв'язків між ними. У якості прикладу розвитку нештатної ситуації наведено можливі сценарії розвитку переходу у некерований політ авіаційної керованої ракети класу «повітря-повітря».

Ключові слова: імовірнісна функція, керовані засоби ураження, надійність, нештатна ситуація, працездатний стан, складова частина, складна технічна система, функція алгебри логіки.

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