PRINCIPES AND REQUIREMENTS FOR THE PROTECTION OF CIVILIAN INFRASTRUCTURE FROM THE DEVASTATING EFFECTS OF AIR ATTACK

Heorhii Dementiiuk¹
Maksym Iasechko²
Sergiy Kolesnichenko³
Kostiantyn Polianskyi⁴
Oleksandr Basarab⁵
Kostiantyn Horbachov⁶
Oleksanndr Yanenko⁷
Ihor Zaitsev⁸

ABSTRACT

Objective: the solution of an important scientific and applied task - to reduce the level of destructive impact of air attack means on life support objects to the maximum permissible level and to create complex protection of life support objects from the destructive effect of air attack means of attack.

Theoretical background: considered and analyzed the use of air attack means and the destructive impact on civil infrastructure in the conditions of the Russian-Ukrainian war, tactical and technical characteristics, application options and priority. The principles and requirements for means of protection of civil infrastructure have been developed. The task of further research is defined.

Methodology: determined by a complex of scientific research tasks and carried out using: methods of system analysis, methods of numerical modeling.

Results and Discussion: may be useful: in the development of principles for the use of means of protection from the destructive impact of various means of air attack; in the development of new and improvement of existing methods of reducing the impact of means of air attack on critical infrastructure facilities to the maximum tolerable level.

Conclusion: the conducted research will make it possible to formulate scientifically based recommendations for ensuring the protection of critical infrastructure objects from the destructive impact of various types of air attack means.

¹ Ivan Kozhedub Kharkiv National Air Force University, Kharkiv, Sumska, Ukraine. E-mail: g_dementiiuk87@gmail.com Orcid: https://orcid.org/0000-0002-8770-8479
² Ivan Kozhedub Kharkiv National Air Force University, Kharkiv, Sumska, Ukraine. E-mail: maxnik8888@gmail.com Orcid: https://orcid.org/0000-0001-5643-0059
³ Donbas National Academy of Civil Engineering and Architecture, Kramatorsk, Donetsk Oblast, Ukraine. E-mail: kolesnichenko@gmail.com Orcid: https://orcid.org/0000-0001-5087-8354
⁴ Donbas National Academy of Civil Engineering and Architecture, Kramatorsk, Donetsk Oblast, Ukraine. E-mail: polianskyi@gmail.com Orcid: https://orcid.org/0000-0002-7615-3975
⁵ National Academy of the State Border Guard Service of Ukraine named after Bohdan Khmelnytsky, Kramatorsk, Donetsk Oblast, Ukraine. E-mail: basarab@gmail.com Orcid: https://orcid.org/0000-0002-2852-9534
⁶ National Defense University of Ukraine named Ivan Cherniahyovsky, Kyiv, Kyiv, Ukraine. E-mail: horbachov@gmail.com Orcid: https://orcid.org/0000-0001-7931-1028
⁷ National Defense University of Ukraine named Ivan Cherniahyovsky, Kyiv, Kyiv, Ukraine. E-mail: yanenko@gmail.com Orcid: https://orcid.org/0000-0002-8552-7543
⁸ Donbas National Academy of Civil Engineering and Architecture, Kramatorsk, Donetsk Oblast, Ukraine. E-mail: zaitsev@gmail.com Orcid: https://orcid.org/0000-0002-3084-8067
Originality/value: increasing the degree of protection of critical infrastructure objects from air attack means with radar correlation-extreme guidance algorithms.

Keywords: Radio Electronic Means, Electromagnetic Radiation, Critical Infrastructure, Cruise Missile, Electromagnetic Shield, Protection Technologies.

1 INTRODUCTION

Given the experience of combat use of cruise missiles spanning six and a half decades, they can be considered a mature technology that has proven itself well. During their existence, there has been a significant development in the technologies used in the creation of cruise missiles, covering the airframe, engines, means of defeating air defenses and navigation systems.

Thanks to the technologies of creation, rocket gliders became more and more compact. Now they can be placed in the internal compartments and external suspensions of aircraft, tube-type ship launchers or submarine torpedo tubes.
Air defense countermeasures emerged in the 1960s as air defense systems became more effective. These include low altitude flight with contouring of terrain or rocket flight at an extremely low altitude above the sea surface in order to hide from radars, and increasingly their shape increases inconspicuousness, and the use of radio-absorbing materials is designed to reduce radar visibility.

The basic idea of all cruise missiles is that these weapons can be launched at a target beyond the range of enemy air defense systems in order not to expose the launch platform to a retaliatory attack.

The first combat cruise missile was the German FZG-76/V-1, more than 8,000 of which were used, mostly against targets in Great Britain (Turinskyi et al., 2019). Judging by modern standards, its navigation system was quite primitive: the gyroscope-based autopilot maintained the course, and the anemometer the distance to the target. The missile was set on a planned course before launch and the estimated distance to the target was displayed on it, and as soon as the odometer indicated that the missile was above the target, the autopilot took it into a steep dive. The missile had an accuracy of about a mile and this was enough to bomb large urban targets such as London. The main purpose of the bombing was to terrorize the civilian population and divert the British military forces from offensive operations and direct them to perform air defense tasks.

In the 1950s, the first conventional post-war tactical cruise missiles entered service, primarily as an anti-ship weapon. While on the marching part of the trajectory, guidance continued on the basis of the gyroscope, and sometimes was corrected by radio communication, the accuracy of guidance on the final part of the trajectory was ensured by a homing head with a short-range radar station, semi-active in early versions, but soon replaced by active radars. Missiles of this generation usually fly at medium and high altitudes, diving when attacking a target.

In the 1960s, there were significant improvements in the accuracy of inertial systems, and the cost of such equipment also increased. As a result, this has led to conflicting demands for accuracy and cost. As a result, a new technology emerged in the field of cruise missile navigation, based on the system of determining the location of the missile by comparing the radar mapping of the area with the reference mapping program. This technology entered the service of US cruise missiles in the 1970s and Soviet missiles in the 1980s. TERCOM technology (Digital Correlation System with Terrain Terrain of the Cruise Missile Guidance Unit) was used, as was the astronavigation system, to zero out the cumulative inertial system errors.

The experience of the enemy in the Russian-Ukrainian war using cruise missiles with a radar guidance method to destroy civilian critical infrastructure in Ukrainian cities showed that standard means of air defense are not always effective in combating this type of weaponry. There is a need to use other methods to physically destroy such targets.

The purpose of the article is to analyze the destructive impact of cruise missiles on critical infrastructure objects, to develop a protection method based on the use of an electromagnetic shield to counter cruise missiles.

2 LITERATURE REVIEW

A large number of works were devoted to the development of methods and means of passive protection of objects, which were carried out and are carried out by such famous scientists as M.Iasechco, O. Sytenko and others. However, the existing methods and means are not able to ensure the necessary effectiveness of the protection of critical infrastructure objects due to their peculiarities, primarily due to the lack of ideal screens (without defects), the impossibility of creating electromagnetic screens or the use of hermetic screens, in relation to
the destructive impact of cruise missiles with the radar method of navigation - insufficient the number of air defenses to protect and the spread of critical infrastructure facilities. Therefore, a contradiction arose, which is caused, on the one hand, by the presence of the destructive effect of cruise missiles with a radar guidance method, and on the other hand, by the lack of technologies, methods and means that will provide the necessary level of protection of the critical infrastructure object without affecting their functioning and which can be implemented at critical infrastructure facilities without significant financial losses and the involvement of air defense means.

3 MATERIALS

The first mass serial cruise missile was created back in the Second World War in Germany - "Fau-1". It was created as a Wunderwaffe - a "miracle weapon" that could turn the tide of war in favor of the Third Reich. It began to be actively used since 1943 for attacks on London with the aim of terrorizing the civilian population (Christopher, 2013).

One of the main difficulties of the development was the guidance system. It looked as simple as possible - the autopilot monitors the course and altitude and measures the flight range. As soon as the "Fau-1" flew the specified distance, the autopilot put the missile into the pike. Later, the Germans developed the first inertial guidance system based on analog devices with a gyroscope and accelerometer for the V-2 ballistic missile.

It should be noted that the accuracy of any inertial system, even a modern one, is limited, it is closed in itself and has exactly only its initial coordinates, and then only calculates them independently, relying on the indicators of the devices. And the longer the inertial system works, the greater the error. And at the level of Western technologies of the 1970s and 1980s, it was about 600 meters per hour of work.

Therefore, it was quite logical to invent a mechanism that would adjust the indicators. TERCOM became this system for cruise missiles that had to fly hundreds of kilometers and stay in the air for hours. Its principle is that the rocket scans the surface below it and compares it with the standard. One of the simplest implementations will be, for example, terrain data - height differences recorded by the rocket's radio altimeter (Dementiiuk et al., 2023).
In this case, the missile route can be divided into certain control points, the map of which is stored in the missile’s memory. They should be areas with contrasting topography, for example, rivers with steep banks, a network of ravines, or even individual large buildings. Having arrived, the rocket compares, locates itself and adjusts the inertial system indicators, resetting the accumulated error.

Currently, the TERCOM system uses not only terrain data, but also visual images. This is due to the fact that the route may not have a characteristic terrain. But this system is much more complex, because it requires work at the level of pattern recognition, but this technology, called DSMAC, was successfully mastered in the United States in the 1980s and integrated into the Tomahawk Block II cruise missile.

The main disadvantage of this system is that the inertial system can launch the missile completely past the control point and the missile will not be able to orient itself. Of course, the more powerful computers became, the larger the volume of maps could be laid, but still the system did not give a 100% guarantee.

The advent of satellite navigation changed the matter dramatically, because now it became possible to constantly receive one's coordinates, altitude and speed. It was for this
that the USA initially began to deploy the GPS system in the 1970s, and in the 1980s the USSR began to deploy its GLONASS.

When conducting an analysis of countering cruise missiles, one should pay attention to the materials of their production, which affect their detection by radar means. During the armed aggression of the Russian Federation against Ukraine, the enemy actively uses modern coatings of the "ZYPISIL 601 RPM-01" type, which make it possible to reduce the effective area of target dispersion. It is able to absorb ultra-high frequency energy and electromagnetic waves and radiation. This sheet is a thin, flexible, silicone (or fluorosilicone) base filled with magnetic nano- and microdisperse powders. The high-frequency absorbing sheet is available in different thicknesses, from 1.0 mm to 10.0 mm. The material "ZYPISIL 601 RPM-01" is an ultra-broadband, heatresistant ultra-high-frequency absorber (absorber of ultra-high-frequency energy, absorber of electromagnetic waves, absorber of ultra-high-frequency radiation). The heat-resistant silicone base gives the material the appropriate properties of flexibility, softness and elasticity. Broadband sheet wave-absorbing material provides high standards of electromagnetic compatibility, ideal for high-tech equipment and ultra-high-frequency devices. The main areas in which this letter is used are the aviation industry, shipbuilding, radar (radioelectronic) equipment and others.

This material is used to protect Soviet-made Kh-55 cruise missiles and its Russian modernization Kh-555, as well as Kh-101 air-to-surface missiles, which additionally makes it impossible to be detected by radio-electronic means for further shooting down by anti-aircraft systems. It becomes more difficult for air defense units to detect them, in most cases, thanks to this material, detection does not occur from the beginning, but at the moment of the launch of the missile.

Regarding the use of cruise missiles by the Russian Federation, the situation is as follows. Aviation X-101 and X-555 have all four components of navigation. Kalibr missiles most likely do not have DSMAC. But in the realities of the Russian Federation, another important factor is the availability of detailed, up-to-date and accurate radar and optical maps that are loaded into the missile’s memory.

Now more and more often, the enemy began to use Kh-59M missiles, the most common of which, most likely, use only inertial and satellite navigation, and for direct targeting, a radar or television guidance system is turned on.

As for the Kh-22, it generally only has an inertial on the march section and a radar guidance system on the terminal. Both with extremely low accuracy on the Soviet technological base of the 1960s and 1970s. That is, it is launched in the direction of the target, which, moreover, should be as radio-contrast as possible.

Figure 2. Appearance of the Kh-22 missile
Source: Kozubenko & Shulman (2022)
The X-22 missile was developed in the 1950s of the last century. Its main task was the destruction of aircraft carriers of the US Army. This is the largest non-nuclear missile currently in service with Russia. The weight of the warhead is 960 kg, and the length is almost 12 m. Other missiles usually have a warhead weight of 200–500 kg and a length of 6–8 m.

Accordingly, the Kh-22 is capable of causing much greater destruction than most modern Russian missiles. But it has a significant drawback - low accuracy.

The highest accuracy was achieved in the mode of active operation of the homing head on the entire flight path. But in this mode, the missile becomes visible to air defense systems at a long distance. Most likely, Russia uses a combined guidance mode: most of the flight, the missile flies autonomously, and only at a certain distance to the target does the homing head turn on. In this mode, the accuracy drops significantly and amounts to several hundred meters, but the chances of interception decrease.

At the same time, the Kh-22 homing radar head is able to recognize only very large objects, such as a large warship or a large bridge.

On December 1, 2022, at a briefing of representatives of the Security and Defense Forces of Ukraine, fragments of the warhead of the Kh-55SM missile, which Russia uses during shelling of Ukraine, were demonstrated (Kozubenko & Shulman, 2022). This is a modification with an increased range of the Soviet Kh-55 aviation cruise missile, which is used by Russia to attack Ukraine from Tu-95 and Tu-160 strategic bombers from March 2022. X-55 and X-555 rockets fly at subsonic speeds with terrain contouring at extremely low altitudes. They are intended for use at stationary strategically important objects (Christopher, 2013; Iasechko, Mozhaiev et al., 2020).

![Figure 3. Appearance of the Kh-55 missile](source)

**Source:** Kozubenko & Shulman (2022)

Basic characteristics of the X-55SM:
- flight range — up to 3,500 km;
- flight speed — 720-830 km/h;
- launch height — 0.6-12 km;
- flight height (on the march) — 40-110 m;
- dimensions — 6×3 m;
- starting mass — 1.5 tons (fuel — 260 kg);
- mass of the combat unit — 410 kg;
- power — 200-500 kilotons;
- accuracy - up to 20 m.

Since the beginning of hostilities, information has appeared about the first use of Kh-59 missiles. This is an old Soviet missile from the 1980s, but it is quite accurate. The circular possible deviation is indicated as less than 10 m, but the USSR and Russia tend to exaggerate the real accuracy of their weapons.

![Figure 4. Appearance of the Kh-59 missile](image)

Source: Kozubenko & Shulman (2022)

The disadvantage of the X-59 is its short range - less than 300 km. That is, it can be applied only in the border areas or in the area of the Black Sea coast. It also carries the smallest charge (up to 300 kg) and cannot destroy a large object.

In order to terrorize and intimidate Ukrainians, Russia strikes almost every day with the help of cruise missiles, in particular the Kalibr cruise missiles, which are launched both from the Iskander aerial operationaltactical complexes and from ships. Launches are carried out beyond the reach of Ukrainian means of destruction.

The Kalibr cruise missile has nothing revolutionary, it is an updated version of the Soviet-developed 3M10 missile, which in turn was a tracing paper from the American Tomahawk cruise missile (Sytenko, 1965; Iasechko, Larin et al., 2020). Its ground version for the RK-55 complex lasted only a few years, and was prohibited by the treaty on the elimination of medium and short-range missiles between the USSR and the USA.

Thanks to this program, Russia created the "short" 3M14 missile (4.8 meters long) and the "longer" 3M54 (7.2 meters long) with a flight range of more than 1,500 km. The last one was tested at the Iskander-K complex in 2009, called R-500, and stated that its range was no more than 500 km and the contract was not violated.
Figure 5. Appearance of the Kalibr missile
Source: Datsenko (2022)

3M54 "Caliber" - missile characteristics:
- Length: 7.2 m (without starting accelerator)
- Wingspan: 3.3 m
- Flight weight: 1320 kg
- Weight of the warhead: 450 kg
- Speed: Mach 0.7
- Flight range: more than 1500 km

The Soviet X-55 and its more modern modification X-555 became an alternative to the Kalibr-type missiles at a longer distance. But these missiles can no longer be called highly accurate. For them, the circular deviation is 20–100 m (Datsenko, 2022).

Russia uses P-800 Onyx cruise missiles to strike targets in southern Ukraine. This missile was developed in the late 1970s as a medium-range anti-ship missile. For export, a missile with a reduced flight range (300 km versus 600 km) is delivered under the name "Yakhont". From open sources, we can calculate that during the entire war, about 40 such cruise missiles were launched (Datsenko, 2022). This is only 10% of the pre-war stockpile of missiles, which numbered up to 400 units. The peculiarity of the rocket is that it is supersonic. This is the only cruise missile that was used in Ukraine, which flies at 2.5 times the speed of sound, and this is the difficulty of intercepting it. The missile flies along a combined trajectory: in the first stage, it reaches a height of 10-14 km, on the approach to the target, it descends to 15 meters above the surface of the sea. The weight of the warhead is 300 kg.
In total, Russia had almost 7,000 medium- and short-range missiles (up to 5,500 km) at the beginning of the war. Almost half of them are low-precision Kh-22, Kh-55 missiles (Kozubenko & Shulman, 2022; Datsenko, 2022).

At the first stage of the war, Russia mostly used Kalibr missiles (sea-based) and Iskander missile complexes. Less than the Kh-101 missile, it has several times announced the use of its latest development, the Kh-47 Dagger.

In the Russo-Ukrainian war, the Kh-101 is used - the latest cruise missile, which is launched from Tu-160 and Tu-95MS missile carriers. It is difficult to detect, intercept and shoot down with the help of air defense means. The peculiarity of this cruise missile is that it is able to change the target even when it is in flight. The development of the missile was completed in 2013, it has a long flight range, claimed to be 7,000 kilometers, as well as the use of stealth technology, which makes it quite difficult to intercept. At the same time, the
Kh-101 is based on the Kh-555, which in turn is based on the Soviet Kh-55, which was adopted in 1983.

![Image of Kh-101 missile](image)

**Figure 8.** Appearance of the Kh-101 missile  
*Source: Datsenko (2022)*

The inertial navigation system with a gyro-stabilized platform (Figure 9) is a mechanical three-axis gyro stabilizer in a gimbal suspension (Figure 10).

![Image of inertial navigation system](image)

**Figure 9.** Inertial navigation system. General appearance  
*Source: Turinskyi et al. (2019)*
The equipment of users of satellite navigation systems is designed to provide the control system with the current values of coordinates (latitude, longitude, altitude), projections of the velocity vector of the cruise missile based on the signals of the satellite navigation systems GLONASS and GPS along the flight route of the cruise missile, regardless of meteorological conditions (Skoblikov & Knyazev, 2012).

The receiving and computing unit (Figure 11) is installed in the nose part of the fuselage of the cruise missile under the inertial system unit.
The receiving and computing unit provides: solving a navigation problem in coordinate systems; measurement of navigation parameters with the following dynamic characteristics of object movement: speed up to 1000 m/s; height up to 15,000 m. automatic, continuous, real-time detection and issuance of:

- coordinates of the object;
- height;
- three components of the velocity vector;
- current time scales;
- root mean square value of the predicted accuracy of location coordinates.

The main technical characteristics of the navigation system:

- 24 parallel reception channels:

  Coordinate/height determination error in combined mode of operation (GLONASS and GPS) – 15 m; error of determining the velocity vector in the combined mode of operation (GLONASS and GPS) – 0.3 m/s; the time of a reliable solution to a navigation task at a cold/warm start – no more than 90/60 s; information update rate - from 1 to 10 Hz; power consumption, slightly more than 10 W; power supply voltage of the module - +27V; overall dimensions 182×140×58 mm; the mass of the block is no more than 1.3 kg.

As part of the navigation system, the optical-electronic system provides accurate determination of the current coordinates of the cruise missile in flight, and, if necessary, issuing signals to correct the parameters of the on-board inertial control system (Iasechko, Sachaniuk-Kavets’ka et al., 2020). The optical-electronic system is an autonomous system that provides navigation in geophysical fields, in particular, by the appearance of the terrain over which the cruise missile flies (Iasechko, Larin et al., 2019).

The system uses the optical contrast of the terrain in the visible range. Thanks to the high informativeness of the optical image, navigation can be ensured over almost any, including orientationless terrain (except water surface).

The system uses algorithms of correlation-extreme methods, which are based on an in-depth analysis of the mutual location of maxima, comparing the current and reference images with the use of several pictures obtained in different seasonal conditions as reference information about the area.

Thus, the creation of means of protection of critical infrastructure objects, taking into account the main characteristics, features of the application and functioning of cruise missiles with radar correlation-extreme guidance algorithms, should be aimed at the optimal combination and implementation of the following principles:

- lack of influence of protection means on the process of functioning of critical infrastructure objects;
- instant reaction of the application (ensuring the required speed, taking into account the notification of the launch of a missile strike);
- energy independence or minimum acceptable energy costs;
- multiple use;
- distortion of the reference image of the critical infrastructure object, which is used as the initial information of the cruise missile navigation system;
- allowable increase in the weight and overall characteristics of the critical infrastructure object;
- practical implementation and possibility of application in urban conditions.
The implementation of these principles is aimed at increasing the effectiveness of protecting critical infrastructure objects from the destructive impact of cruise missiles with radar correlation-extreme guidance algorithms.

The creation of means of protection of critical infrastructure objects, taking into account the main characteristics, peculiarities of the use and functioning of air attack means, should be aimed at the optimal combination and implementation of the following principles:

- lack of influence of protection means on the process of functioning of critical infrastructure facilities;
- instant reaction of the application (providing the necessary speed code, taking into account the notification of the launch of a missile strike);
- energy independence or minimum acceptable energy costs;
- multiple use;
- distortion of the source information of the critical infrastructure object, which is used as a reference image of the cruise missile navigation system;
- allowable increase in the weight and overall characteristics of the critical infrastructure object;
- practical implementation and possibility of application in urban conditions.

The main requirements for the means of protecting civil infrastructure objects from the destructive impact of air attack means are:

1. High speed.
2. Active use of an electromagnetic shield over civil infrastructure objects
3. Minimum mass per unit area.
4. High strength characteristics.
5. Resistance of the frequency range \( \lambda = 3 \, \mu \text{m}, \lambda = 8 \, \mu \text{m} \).
6. Changing the reference image of the cruise missile navigation system by changing the radar signal reflected from the object.

Considering the above, the most complete requirements for critical infrastructure facilities to protect against the destructive impact of cruise missiles can be satisfied with the use of protective electromagnetic shields (Iasechko, Kolmykov et al., 2020).

4 CONCLUSIONS

The article analyzes the use of air attack means in the conditions of the Russian-Ukrainian war. The analysis of the application and the experience of combat operations showed that an important direction is the protection of civil infrastructure objects from the destructive impact of air attack means (Annathurai et al., 2023). The cities of Ukraine, in particular Kyiv, Kharkiv, Odesa, Lviv, are subjected to massive missile attacks, there are currently no alternative methods of protecting civil infrastructure objects, so it became necessary to analyze the use of air attack means and develop the principles and methods of their protection (Shalman et al., 2023). Thus, in the article, an important scientific and applied task was set - to reduce the level of the destructive effect of air attack means on life support objects to the maximum permissible level and to create a comprehensive protection of life support objects from the destructive effect of air attack means. When solving the task, the requirements for means of protection were presented and the principles of construction of means of protection were developed, which are the main starting data for the development of methods and models of complex protection of critical infrastructure objects. The results of the work can be useful: in the development of the principles of the use of means of protection against the destructive effect of various means of air attack; in the development of new and improvement of existing methods of reducing the impact of air attack on critical infrastructure objects to the maximum permissible level. The conducted research will make it possible to
formulate scientifically based recommendations for ensuring the protection of critical infrastructure objects from the destructive impact of various types of air attack means. The task of developing a new combined method of protecting critical infrastructure objects was set.

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