УДК 629.78 https://doi.org/10.15407/itm2026.02.010

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AEROSTATIC SYSTEMS IN DEFENSE APPLICATIONS: CURRENT CHALLENGES AND STATE OF THE ART

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Аеростатні системи дирижабельного типу мають більш ніж столітню історію інженерного розвитку та продовжують привертати увагу науково-технічної спільноти в наш час. З одного боку, це можна пояснити тим, що апарати, які легші за повітря, потребують менших витрат палива та бортової енергії на підтримання свого положення в повітряному просторі. З іншого боку, при розробці оптимальних конструкцій дирижаблів, вони можуть стати ефективними у якості засобів перевезення вантажів та платформ для розміщення обладнання різного призначення (науково-дослідного, метеорологічного, військового тощо). Враховуючи це, в роботі проведено аналіз сучасного стану розробки аеростатних і дирижабельних систем різного призначення. На базі цього аналізу виявлено переваги та недоліки застосування апаратів легших за повітря для польотів в щільних шарах атмосфери Землі, а також сформовано перелік проблемних аспектів їх експлуатації для різного призначення. Також показано, що дирижабельні системи можуть бути використані як ефективний елемент систем протиповітряної оборони від небезпечних безпілотних літальних апаратів.

З огляду на це, метою дослідження є виявлення проблемних аспектів проєктування дирижабельних систем для застосування у якості засобів захисту об'єктів критичної інфраструктури України від небезпечних безпілотних літальних апаратів. Так, для досягнення мети, в роботі проаналізовано сучасний стан розвитку матеріалів, з яких виготовляються оболонки і елементи конструкцій сучасних дирижаблів, особливості розробки їх систем навігації та керування, а також вантажопідйомність в залежності від габаритних параметрів аеростата. В результаті цього сформовано технічні вимоги до розробки аеростатних засобів дирижабельного типу для захисту повітряного простору та критичної інфраструктури, а також визначено шляхи для наукових досліджень, що спрямовані на рішення проблемних аспектів проєктування цих систем.

Ключові слова: *аеростатні системи, апарати легші за повітря, безпілотні літальні апарати, аналітичний огляд, дирижаблі.*

Aerostatic systems of the airship type have more than a century of engineering development and continue to attract attention within the scientific and technical community today. On the one hand, this can be explained by the fact that lighter-than-air vehicles require lower fuel consumption and onboard energy to maintain their position in the airspace. On the other hand, optimal airship configurations may be effective means of cargo transportation and platforms for equipment of various purposes, including scientific, meteorological, and military payloads. Considering these factors, this paper analyzes the state of the art in the development of aerostatic and airship systems for various applications. Based on this analysis, the paper identifies the advantages and drawbacks of using lighter-than-air vehicles in the Earth's dense atmosphere and challenges associated with their use for different purposes. It is also shown that airship systems can serve as an effective element of air defense systems against hazardous unmanned aerial vehicles.

In this context, the objective of this study is to identify key challenges in the design of airship systems intended for the protection of Ukraine's critical infrastructure against dangerous unmanned aerial vehicles. To achieve this objective, the paper analyzes the state of the art in the development of materials for envelopes and structural elements of modern airships, the features of navigation and control system development, and the payload capacity depending on the aerostat geometry. As a result, technical requirements for the development of airship-type aerostatic systems for airspace and critical infrastructure protection are formulated, and lines of further research aimed at resolving the key challenges in the design of such systems are identified.

Key words: *aerostatic systems, lighter-than-air vehicles, unmanned aerial vehicles, analytical review, airships.*

Introduction. Aerostatic systems based on lighter-than-air (LTA) technology represent one of the oldest branches of aerospace engineering, yet they continue to attract considerable scientific and engineering attention. Compared with conventional rotary-wing and fixed-wing unmanned aerial vehicles (UAVs), LTA vehi-

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cles require lower on-board energy consumption to maintain their position in the airspace, since the aerostatic lift generated by the displaced air mass supports most or all of the vehicle weight [1]. Depending on the configuration, LTA systems are classified as unpowered – balloons and tethered aerostats – or powered, which include non-rigid, semi-rigid, and rigid airships, as well as hybrid semi-buoyant vehicles [2]. Among these, tethered aerostats are especially attractive for persistent surveillance missions, because the tether simultaneously anchors the platform, supplies electrical power to the payload, and provides a high-bandwidth data link to the ground control station, that significantly reduce the volume and mass of on-board energy storage and propulsion correction systems [3]. The operational cost per flight hour of an aerostat system has been assessed at $20–50, compared with $400–1000 for a helicopter and $1000–30000 for a UAV, making aerostatic platforms one of the most cost-efficient solutions for long-endurance aerial surveillance tasks [4].

The operational value of tethered aerostats in the defense context has been confirmed through extensive military use. Beginning in the 1980s, the U.S. Tethered Aerostat Radar System (TARS) network deployed a series of large aerostats along the southern and south-eastern borders for low-altitude radar surveillance, achieving detection ranges of 220–260 km at operating altitudes of 3000–3500 m [4]. Starting in 2003, the U.S. Army and Lockheed Martin deployed 66 Persistent Threat Detection System (PTDS) aerostats in Iraq and Afghanistan, providing round-the-clock wide-area surveillance that directly reduced casualties among coalition forces [3]. The U.S. Government Accountability Office (GAO) estimated the total DoD investment in aerostat and airship programs at nearly $7 billion from fiscal years 2007 through 2012, reflecting the strategic importance of LTA platforms for intelligence, surveillance, and reconnaissance (ISR) capabilities [5]. The Joint Land Attack Cruise Missile Defense Elevated Netted Sensor System (JLENS), placed on operational service in 2011, demonstrated that two aerostats floating at 3.3 km could control the airspace within a radius of 544 km, detecting cruise missiles, aircraft, and tactical ballistic missiles on the ascending portion of their trajectory, while simultaneously providing fire-control data to surface-to-air missile systems [5]. Israel deployed the large-scale Sky Dew aerostat (approximately 70 m in length) as part of the HAAS surveillance network to counter threats from UAVs, multicopters, cruise missiles, helicopters, and low-flying aircraft [6]. Turkey has supplied its armed forces with the Aselsan Water Drop and Global tethered aerostats specifically designed for cruise missile detection and border protection, and has exported airship and aerostat platforms to Iraq for the protection of strategic facilities and ports [6]. These examples confirm that aerostatic systems of the airship type have evolved from scientific observation platforms into a key element of layered air defense architectures in numerous nations.

The rapid proliferation of small commercially derived attack drones as instruments of asymmetric warfare in the ongoing armed conflict in Ukraine has created an urgent demand for cost-effective, long-endurance aerial platforms capable of protecting critical infrastructure and airspace. As demonstrated by Orlov et al. [6], an aerostat-mounted radar positioned at an altitude of several kilometers provides a line-of-sight detection range for low-flying targets several times greater than that of ground-based systems: when a radar antenna is elevated to 100 m, the detection range of a cruise missile flying at 36 m altitude increases from 35 km to 65 km, nearly doubling the reaction time available to air defense forces. At an altitude of 10 km, the radar horizon extends to approximately 400 km, enabling detection and tracking of up to 100 low-altitude targets at distances of 40–150 km with a radar weight within 200–500 kg, acceptable for installation on large aerostats [6]. Furthermore, electronic warfare equipment and GPS spoofing systems mounted on an aerostat above the flight path of an incoming missile can effectively disrupt its navigation, since the jamming signal is directed from above the protected zone of the anti-jamming antenna array [6]. As shown by Byelyaev et al. [4], the operation of 22 low-altitude detection radars mounted on aerostat platforms could replace 147 conventional ground-based radar units while generating annual savings exceeding one billion hryvnias, demonstrating the economic attractiveness of the aerostat-based approach for the defense needs of Ukraine. More recently, Ukrainian company Aero Bavovna has developed a tethered aerostat capable of ascending to approximately 800 m and carrying up to 10 kg of payload independently of weather conditions; the platform concurrently serves as a communications relay, an electro-optical and thermal imaging surveillance node, a radio-electronic warfare carrier, and — through a novel integration concept — as an elevated launch platform for FPV interceptor drones designed to counter Shahed-type attack UAVs [7]. These developments confirm the unique suitability of aerostatic systems for the protection of the airspace and critical infrastructure of Ukraine against hazardous unmanned aerial vehicles.

The successful design of aerostatic airship-type systems for defense purposes requires the resolution of several coupled technical problems. The first concerns envelope materials: the multi-layer laminate structure of an aerostat hull must simultaneously provide a high strength-to-weight ratio, low gas permeability, resistance to ultraviolet radiation and coastal atmospheric degradation, and adequate flex-fatigue endurance under continuous outdoor deployment [8]. The second concerns the quantitative relationship between hull geometry and payload capacity: buoyant lift scales with envelope volume, so the choice of hull shape, fineness ratio, and ballonet configuration directly governs the disposable load available for radar, optical, and electronic warfare systems [9]. The third concerns station-keeping under wind loading: a tethered aerostat develops complex aerodynamic forces, tether tension, and pitch trim that must be analyzed through equilibrium modeling and managed through appropriate tether management and ballonet pressure control [9]. The fourth concerns aerodynamic shape optimization: the conventional body-of-revolution (BOR) hull has well-understood drag characteristics, but multi-lobed and hybrid configurations offer improved aerodynamic efficiency and payload capacity at the cost of more complex flow physics that require careful computational fluid dynamics (CFD) analysis [8, 9].

In Ref. [1], Manikandan and Pant present a comprehensive review of hybrid airship research covering conceptual design, aerodynamics, structural analysis, dynamics, and thermal modeling, demonstrating that the field has advanced substantially since mid-century. The limitation of this work is that it focuses on free-flying hybrid vehicles and does not address tethered aerostat systems or defense-specific operational requirements. The article [2] by Dasaradhan et al. reviews the textile and polymeric materials used for aerostat envelope construction, examining load-bearing fibers, gas barrier films, environmental protection layers, and joining techniques; high-performance Vectran liquid-crystal polymer fabric and polyurethane-based laminates are identified as the most suitable candidates. The shortcoming of this work is that it does not link material properties to envelope sizing or to defense system-level constraints. The paper [5] by Kumar et al. describes the full design cycle, stress analysis, and flight-trial validation of a 2000 m³ tethered aerostat with 300 kg payload capacity at 1 km altitude, presenting an iterative sizing methodology, finite element analysis, and tether profile estimation. The study is limited to a single tactical-class BOR configuration and does not address multi-lobed hull geometries or counter-UAV mission requirements. The article [8] by Carrión et al. presents a RANS CFD study of the Airlander multi-lobed hybrid air vehicle, demonstrating that fins, leading-edge root extensions, and strakes contribute more than half of the total dynamic lift at high pitch angles and have a significant stabilizing effect on the pitching moment. This work addresses only a free-flying commercial hybrid airship and does not consider tethered operation. The paper [9] by Pai and Manikandan provides a systematic CFD comparison of conventional single-lobed and multi-lobed (bi- and tri-lobed) airship configurations using the k-ε turbulence model; the tri-lobed Garg-profile configuration is found to exhibit the highest lift-to-drag ratio, while bi-lobed designs show a (47–69) % increase in drag coefficient relative to conventional designs at the same hull volume. The shortcoming of this study is that it does not extend to tethered system design, payload-to-volume scaling, or defense applications. In Ref. [4], Byelyaev et al. systematically analyze world experience in the application of military aerostat aircraft and formulate prospective directions for their use in the Armed Forces of Ukraine, covering radar surveillance, border control, communications relay, and mine detection. The limitation of this work is that it does not address structural and aerodynamic design methodology for airship-type aerostats, nor does it consider the specific threat environment posed by modern attack UAVs.

The main shortcomings of the existing studies can be summarized as follows: 1) the design of envelope materials, hull geometry, and navigation and station-keeping systems is typically studied in isolation, without a system-level analysis linking these aspects to defense-specific operational requirements for the protection of critical infrastructure; 2) the application of aerostatic airship-type systems as a means of protection against hostile UAVs — a threat that has become acute following Ukraine's experience since 2022 — has not been systematically studied, and the corresponding technical requirements have not been formulated.

The objective of the present article is to identify the key design challenges of tethered aerostatic airship-type systems intended for the protection of critical infrastructure and airspace of Ukraine against hazardous unmanned aerial vehicles, and to formulate technical requirements for their development. To achieve this objective, the paper analyzes the current state of development of envelope materials and structural elements of modern aerostats, studies the dependence of payload capacity on the geometric parameters of the aerostat envelope, examines the features of navigation and station-keeping system design for tethered LTA platforms, and identifies promising directions for further research.

The paper is organized as follows. Section 2 reviews the current state of envelope materials and structural elements used in modern aerostatic systems. Section 3 analyzes the payload capacity as a function of aerostat geometric parameters and examines the flight control approaches applicable to tethered airship-type platforms. Section 4 formulates technical requirements for the development of aerostatic airship-type systems for airspace and critical infrastructure protection. The main conclusions are summarized in the final section.

The analysis of the envelopes and structural elements. The main components of aerostat systems include the envelope, gondola, load-bearing frame (suspension lines and structural tapes), suspension nodes, cable attachment systems, ballast systems, and stabilizers.

The envelope is the key element of an aerostat system. It ensures the gas-tightness of the lifting gas chamber, defines aerodynamic characteristics, and largely determines the overall service life of the vehicle [10]. The envelope geometry also affects stress distribution and the structural strength of the system as a whole. Therefore, the selection of the envelope shape must account for multiple factors, including lift generation, aerodynamic drag, and stability in wind flow conditions.

The most common aerostat configurations include spherical, ellipsoidal, teardrop-shaped, and hybrid designs [5, 11, 12]. The choice of geometry depends on the intended mission of the aerostat. To improve aerodynamic stability, a spherical front section is often combined with a teardrop-shaped or kite-like tail (similar to a kite), as seen in systems such as Helikite and TARS 420K. This configuration reduces drag and significantly improves stability in atmospheric conditions while also providing additional aerodynamic lift under crosswind conditions. Considering torsional moments and transverse loads, stabilizing surfaces such as fins or stabilizing tails made from the same envelope material are often integrated into the design [12, 13].

A critical aspect is the selection of envelope materials, which must combine low mass with high strength, thermal stability, gas impermeability, and resistance to ultraviolet radiation and environmental degradation.

Typically, multilayer composite materials are used, including polyester, nylon, Lavsan, and polyurethane-coated fabrics reinforced with Kevlar or other high-strength fibers. Each layer of the envelope performs a specific function (Fig. 1) [2, 10, 14 – 18]:

The load-bearing layer consists of high-performance synthetic fibers, most commonly aramid (Kevlar), polyester (Dacron, PET), liquid crystal polymer (Vectran), and ultra-high-molecular-weight polyethylene (UHMWPE). These synthetic fibers provide a significantly higher strength-to-weight ratio compared to earlier cotton-based fabrics. This layer provides the primary tensile strength of the envelope and exhibits high resistance to tearing, abrasion, and impact loading [17,18]. Such fabrics typically have a density of approximately (1–1.5) g/cm^3. Mechanical properties vary significantly depending on the material; therefore, selection depends on operational requirements. For high-strength fibers (aramid, UHMWPE, LCP), the elastic modulus ranges from approximately (70–130) GPa, with tensile strength up to (2.5–4) GPa, whereas polyester fibers exhibit lower values, with an elastic modulus of (8–12) GPa and tensile strength of (0.7–1.4) GPa.

The gas barrier layer is a thin polymer film or laminate (polyethylene terephthalate PET/Mylar, EVOH, PVDC, polyamide, or polyimide Kapton) that seals the pores of the fabric and retains the lifting gas. It provides sufficient mechanical strength at low thickness and exhibits low gas permeability. This layer must ensure strong adhesion to adjacent layers [13,18]. The glass transition temperature of these materials must also be considered, as it defines the transition to a rigid, glassy state.

The protective layer is an outer coating designed to protect against ultraviolet radiation, atmospheric exposure, and other environmental factors. It is typically a thin layer of polyvinyl fluoride (PVF, Tedlar) or polyvinylidene fluoride (PVDF), sometimes with aluminum metallization. For example, in the TARS project, the envelope uses a PU-coated PVF (Tedlar) system, providing solar resistance and stable performance across a wide temperature range (−72°C to +107°C) [18]. These polymers exhibit high chemical stability and excellent UV resistance.

Adhesive or intermediate layers consist of polyurethane or silicone-based adhesives that bond the structural layers and eliminate voids.

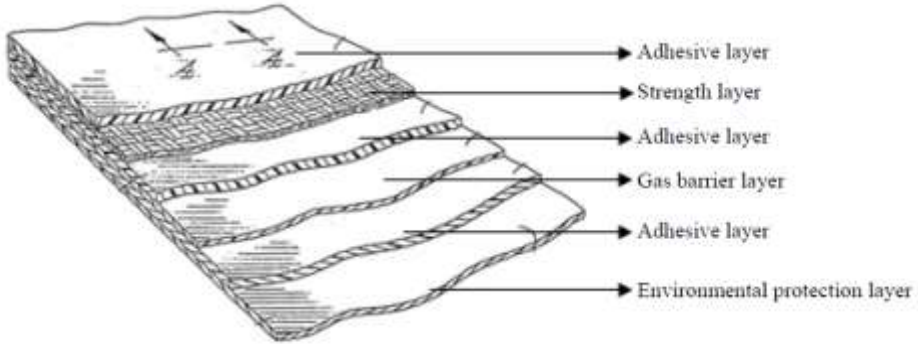

Fig. 1 – Multi-layer structure of typical hull material

In regions of abrupt geometric transitions (nose section, wing-like extensions, or tether attachment points), local stress concentrations may arise. Therefore, smooth conical transitions and rounded edges are used in structural design, particularly in reinforced seam regions. The choice of materials for load-bearing elements critically influences the overall strength and reliability of the system.

Key load-bearing elements include [5, 13]:

Suspension lines and structural tapes are high-performance synthetic cables or woven straps made of aramid (Kevlar, Vectran) or UHMWPE (Dyneema). They distribute the lifting force of the envelope either to the gondola via load tapes or directly to the tether system. Structural tapes reinforce the upper part of the envelope, while suspension lines connect reinforcement patches to the gondola.

The gondola and payload platform consist of lightweight structures made of aluminum, carbon fiber, or composite materials and carry the payload (sensors, equipment, power systems). For example, Sheldahl employed a welded aluminum truss suspended beneath the envelope. In the TARS system (USA), the gondola is attached to the lower structural frame and houses a generator rotor, electronics, and a fuel or storage tank.

Suspension nodes are reinforced attachment points where suspension lines connect to the envelope. Load redistribution is achieved using specialized load-spreading tapes or parabolic stitching patterns. In the Sheldahl system, parabolic reinforcement patterns were used to avoid stress concentrations in seam regions.

Stabilizers are additional lifting or control surfaces made from the same fabric material as the envelope. They are typically located at the tail section and ensure directional stability under wind loading.

Metallic and composite components (aluminum rings, fasteners, and duralumin strips) are used only at structural reinforcement points where rigidity is required. For example, suspension points may be reinforced with aluminum hoops or phenolic (Bakelite-based) stiffening elements.

Envelope panels are cut from roll-based composite fabric sheets, typically using wedge-shaped or segmental circular templates. Panel joining is performed using thermal impulse welding or ultrasonic welding to form airtight seams. Reinforcement tapes are sewn or bonded along seam lines, and seams are sealed with polyurethane or epoxy-based compounds. Double bonding (tapes applied on both sides of the seam) increases reliability.

Maintainability is achieved through modular replacement of damaged sections: the affected area is cut out together with adjacent seams and replaced with a new patch using identical technology. Anti-corrosion and anti-static coatings applied to mechanical joints and textile structures extend service life.

Military applications of aerostat systems impose significantly stricter requirements [2, 13, 15]:

Wind resistance: the envelope and suspension lines must withstand gusts up to (30–40) m/s (approximately (60–80) knots) in tethered operation. A safety factor of 2–3 relative to design loads is typically applied. Reinforcement tapes and seams must withstand repeated cyclic loading induced by wind oscillations. This is achieved through heat-treated fabrics and bias (diagonal) reinforcement along the longitudinal axis.

UV and environmental resistance: the outer coating based on PVC, PVF, or TPU protects against ultraviolet radiation and ozone exposure. Typical service life is 5–10 years without significant loss of gas tightness.

Icing: the envelope surface is designed to have low wettability, and fluoropolymer additives reduce ice adhesion. Some systems include heating or vibration-based de-icing mechanisms.

Gas tightness and self-sealing: metallized coatings (e.g., aluminum-coated PET film) reduce gas leakage. In case of puncture, self-sealing compounds or patching systems are used.

Fire resistance: most aerostat envelope materials are inherently flammable. Therefore, fire-retardant coatings or additives (boron compounds, flame retardants) are applied in critical applications.

Further development of aerostat systems involves advanced materials such as nanocomposite coatings (graphene, nanoclays, and carbon nanotubes), aimed at reducing mass and improving barrier properties. Structural optimization, including topology optimization and variable-thickness laminates, helps reduce stress concentrations within the envelope.

Simulation of 6-dof motion and flight control problem analysis. The payload-to-size ratio represents a critical design parameter for aerostatic systems. Thus, an increase in payload mass leads to a corresponding increase in aerostat volume, which in turn amplifies aerodynamic perturbative forces and necessitates more powerful thrusters for motion control. Conversely, the use of power units with greater thrust leads to a further increase in the airship’s total weight. The problem of optimal airship configuration design, considering payload constraints, is addressed in [5]. The authors demonstrate that the determination of optimal airship design parameters requires comprehensive analyses of the aerodynamic characteristics of the airship hull, as well as structural strength calculations, taking into account payload mass, operating altitude, and flight dynamics. The study also justifies the use of approximate analytical models for obtaining preliminary estimates of airship parameters at the early stages of design. However, it is noted that such estimates are only initial and require further refinement through the application of finite element methods for improved aerodynamic and structural analysis, as well as 6-DoF models for flight dynamics and controllability assessment.

In turn, [19] shows that the analysis of flight dynamics for complex airship configurations with cable connections and structural attachments requires the use of comprehensive mathematical models. In particular, [19] places special emphasis on the mechanics of cable-based airship systems, as well as on aerodynamics and wind loads, which constitute critical factors affecting the flight of such configurations. However, the proposed model is not fully universal for all types of airship and aerostatic systems and is primarily applicable to configurations such as that shown in Figure 2.

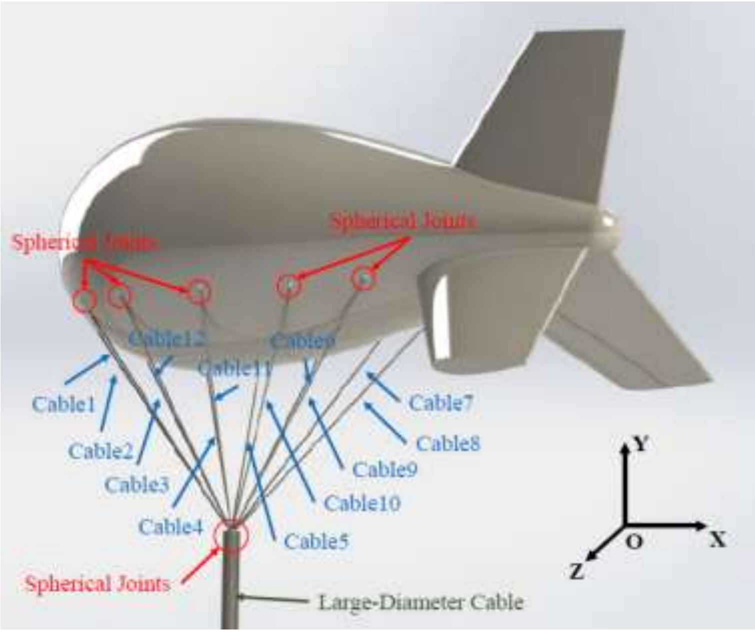

Fig. 2 – Layout details of the tethered balloon cable system [19]

Particular attention in airship flight analysis is given to the optimization of its geometry in terms of aerodynamic performance and mission requirements [20]. It is shown that airships can be classified into the following categories: non-rigid, rigid, heavy-lift vehicles, high-altitude airships, and hybrid airships, each of which has specific requirements for structural design and dynamic characteristics. The study also shows that a key aspect in determining design parameters is the full 6-DoF dynamic modeling, taking into account fully computed aerodynamic coefficients, a defined control law, and the characteristics of control aerodynamic surfaces. Thus, a wide range of methods exists for estimating the aerodynamic coefficients of airships, including analytical approaches [21], semi-empirical [19, 22] methods, and classical CFD techniques [23]. In turn, analytical and semi-empirical methods for aerodynamic coefficient estimation are reasonable to apply during the preliminary stages of design parameter determination, whereas CFD methods are more appropriate immediately before flight testing. In Ukraine, a detailed description of semi-empirical methods for aerodynamic coefficient estimation is presented in monograph [22]. The work presents analytical relationships for determining drag and lift coefficients using a method based on the approximation of historical trends in the evolution of various airship components over previous years. According to [22], this method made it possible to estimate the airship drag coefficient with an error of up to 5 %. However, the work also indicates that other lift, side-force, and moment coefficients require refinement through empirical methods, taking into account the position of the airship relative to the ground surface, propeller wake effects, and other factors.

As can be seen from previous publications, analytical and semi-empirical methods are valid only within a relatively narrow range of angles of attack and sideslip, typically up to 10–30 degrees [21, 22]. This makes it possible to evaluate airship dynamics only in the vicinity of small deviations from the aerodynamic equilibrium attitude. Such limitations do not allow for a full assessment of 6-DoF airship motion and dynamics, especially under nonlinear wind disturbances. Thus, a comprehensive simulation of airship flight ultimately requires the determination of aerodynamic characteristics using CFD methods.

Another challenging aspect is the determination of added masses and added moments of inertia of the airship [24]. Unlike traditional aircraft, for airships the effect of the displaced air mass may be comparable to the vehicle's own mass, which can significantly alter its dynamic characteristics. Currently, several methods exist for determining added masses and added moments of inertia. Among them are methods based on the formulas of Horace Lamb and Max Munk, which are applicable only to simple geometries such as spheres, ellipsoids, or oblate spheroids and are not suitable for the complex configurations of hybrid airships [24]. Also, according [24] for symmetric configurations, some coefficients may be equal to zero; however, nonzero cross-coupling terms still remain, reflecting the interaction between vertical motion, longitudinal acceleration, and pitch. In addition, the added masses strongly depend on the hull shape and flight conditions, with the largest effects typically observed in the vertical direction and in pitching motion due to the large projected area of the airship hull. Another challenge is that the added mass coefficients vary near the ground during take-off and landing, where ground effect can reduce some of these coefficients by approximately half compared to cruise conditions. To address these difficulties, the authors proposed the use of a CFD-based method with a dynamic mesh technique for determining the full added mass matrix of the airship, which remains a highly challenging task.

In turn, the equations of the 6-DoF dynamic model of the airship can be written as follows:

$$\begin{aligned} &(mI_3 + M_A)\frac{d\mathbf{V}}{dt} + m(\boldsymbol{\omega}\times\mathbf{V}) + \boldsymbol{f}_{A,t}(\mathbf{V},\boldsymbol{\omega}) = \mathbf{F_g} + \mathbf{F_B} + \mathbf{F_{aer}} + \mathbf{F_T}, \\ &(J + J_A)\frac{d\boldsymbol{\omega}}{dt} + \boldsymbol{\omega}\times(J\cdot\boldsymbol{\omega}) + \boldsymbol{f}_{A,r}(\mathbf{V},\boldsymbol{\omega}) = \mathbf{M_{aer}} + \mathbf{M_B} + \mathbf{M_{aer.contr}} + \mathbf{M_T}, \end{aligned} \tag{1}$$

where m is the mass of the airship; M_A is the translational added mass matrix [25]; $\mathbf{V} = \begin{bmatrix} V_x & V_y & V_z \end{bmatrix}^T$ is the translational velocity vector expressed in the body-fixed reference frame; $\boldsymbol{\omega} = \begin{bmatrix} \omega_x & \omega_y & \omega_z \end{bmatrix}^T$ is the angular velocity vector expressed in the body-fixed reference frame; J is the rigid-body inertia tensor of the airship; J_A is the rotational added-inertia tensor [25]; $\boldsymbol{f}_{A,t}(\mathbf{V},\boldsymbol{\omega})$ is nonlinear translational added-mass coupling term; $\boldsymbol{f}_{A,r}(\mathbf{V},\boldsymbol{\omega})$ is the nonlinear rotational added-mass coupling term; $\mathbf{F_g}$ is the gravitational force vector with respect to the body-fixed reference frame; $\mathbf{F_B}$ is the buoyancy force vector with respect to the body-fixed reference frame; $\mathbf{F_{aer}}$ is the aerodynamic force vector with respect to the body-fixed reference frame; $\mathbf{F_T}$ is the propulsion force vector with respect to the body-fixed reference frame; $\mathbf{M_{aer}}$ is the aerodynamic moment vector with respect to the body-fixed reference frame; $\mathbf{M_B}$ is the buoyancy-induced restoring moment vector with respect to the body-fixed reference frame; $\mathbf{M_{aer.contr}}$ is the aerodynamic control moment vector with respect to the body-fixed reference frame; $\mathbf{M_T}$ is the propulsion-induced moment vector with respect to the body-fixed reference frame.

Thus, as can be seen from the structure of the input parameters of Eqs. (1), airship flight modeling is a rather complex task from the viewpoint of obtaining adequate initial data for aerodynamic coefficients, added-mass and added-inertia coefficients, as well as the displacement between the center of buoyancy and the center of mass. The determination of these parameters requires extensive CFD analyses and detailed airship structural design, which in turn implies the need for a full range of relevant specialists and equipment. Taking this into account, at the initial design stages and during preliminary assessments, it is reasonable to employ analytical and semi-empirical formulas to estimate the above-mentioned parameters for classical airship geometries [19, 21, 22]. However, when performing comprehensive pre-flight 6-DoF simulations, such as Software-in-the-Loop and Hardware-in-the-Loop simulations, a complete aerodynamic model of the airship is required, including full added-mass and added-inertia parameters, aerodynamic coefficients, and turbulence effects.

General technical requirements for the development of aerostatic airship-type systems for airspace and critical infrastructure protection. The military use of balloons and airships has a long history dating back to the First World War. Modern aspects of their application for defense purposes were discussed in the first section of this paper. Considering these features, balloon and airship systems may be conventionally divided into *active and passive ones*.

Active systems emerged as early as the First World War and were represented by manned bomber airships such as the Zeppelin LZ 1. *Passive* systems, in contrast, were widely employed during both the First and Second World Wars, particularly on the Eastern Front, to protect Soviet cities from attacks by heavy fighters and bombers. These systems generally consisted of tethered balloons filled with hydrogen and connected to the ground by cables, thereby creating aerial obstacles for enemy strike aviation. In addition, a collision between an aircraft and such a barrier could lead to the ignition or detonation of the gas contained in the balloon, which could destroy the aircraft and potentially damage nearby aircraft through the resulting blast wave during massed air raids.

In turn, the development of microprocessor technology, robotics, and electronics has led to the emergence of a new subclass of balloon and airship systems, namely unmanned systems. Thus, the deployable balloon-based apertures, aerial reconnaissance platforms, and communication relay systems described in the first section may also be classified as active systems in the form of *unmanned controlled balloons and airships*.

Modern wars, such as the Russian invasion of Ukraine and conflicts in the Persian Gulf region, demonstrate the extensive use of unmanned strike drones, which are often orders of magnitude cheaper than the available air defense systems, with the exception of machine-gun-based weapons employed by mobile fire groups in Ukraine. Such an imbalance in military economics places the defending side in a disadvantaged position in terms of resource and financial expenditure on air defense. Consequently, there is a need to identify optimal means of protection against unmanned strike aerial vehicles. One of such solutions may be based on balloon and airship technologies implemented using modern technological capabilities, including microprocessors, robotics, and autopilot systems. Thus, both active airship-based systems and passive balloon-barrier systems may be employed to protect critical infrastructure facilities and populated areas against unmanned strike aerial vehicles. So, generalized technical requirements for both active and passive systems may be formulated according to their intended military purpose.

Passive systems are expedient to deploy in the vicinity of critical infrastructure facilities or other protected targets. Such systems may be used either as aerial mines, similarly to those employed during the Second World War, or as platforms for deploying additional obstacles for strike UAVs, such as nets. In this case, the general technical requirements for such systems include:

- determination of the wind resistance limits and tether loads under different wind gust conditions, with recommended operability in winds within the range of (0–20) m/s;
- minimization of deployment and recovery time during operation;
- determination of the optimal number of balloons required for a given protected object, taking into account the specific system type, such as aerial mines or net-based barriers;
- determination of the structural strength characteristics of fastening elements and barrier nets while minimizing the overall system mass.

Active systems, in turn, may be employed as unmanned mothership-type aerial platforms carrying interceptor drones and lightweight air-to-air missiles. Such vehicles may patrol in the vicinity of protected regions at a considerable distance from the line of combat contact and serve as an effective means of intercepting swarms of strike UAVs outside populated areas. In addition, «loitering» airborne platforms are significantly less vulnerable to long-range ballistic missile strikes compared to deployed ground-based air defense systems. Accordingly, loitering airship-based carriers of interceptor drones or lightweight missiles should be specifically designed for sustained patrol operations, which imposes the following key technical requirements:

- flight endurance should satisfy the requirements of the combat mission, for example, rapid launch following the detection of enemy strike UAVs and transit to the estimated interception area;
- sufficient resistance to wind gusts during flight;
- requirements for the propulsion system, which must be capable of compensating for wind perturbations under different flight conditions, including patrol and station-keeping modes;
- the use of onboard power-generation capabilities, such as flexible solar panels, together with hybrid propulsion systems in order to minimize the overall mass of the airship;
- requirements for control aerodynamic surfaces to ensure stable and controllable flight under various operating conditions and determined range of wind perturbations.

Thus, general technical requirements for balloon and airship systems intended for the protection of infrastructure facilities against unmanned aerial vehicles have been formulated. In turn, detailed technical requirements for such systems should be developed on the basis of the tactical and technical characteristics of the attacking unmanned systems, as well as the specific features of the protected infrastructure facility.

Conclusions. Thus, the analysis of the current state of balloon and airship applications has shown that these lighter-than-air vehicles continue to be actively employed in modern projects of various purposes. With the development of science and technology, lighter-than-air vehicles have acquired additional capabilities compared to their early twentieth-century predecessors, namely:

– the emergence of new aerodynamically optimized geometrical configurations for balloon and airship structures;

– advances in materials science have enabled the use of lighter yet simultaneously stronger structural materials for balloons and airships;

– balloons and airships are being considered for active military applications of various kinds, ranging from reconnaissance stratospheric apertures to mothership-type aerial platforms;

– unmanned systems, microprocessor technology, and modern avionics have once again made balloons and airships attractive for the development of unmanned lighter-than-air vehicles.

However, one of the main challenges in the design of modern controlled airships with different geometrical configurations remains the accurate determination of their aerodynamic characteristics and added-mass and added-inertia parameters. Modern approaches, including analytical, semi-empirical, and CFD-based methods, provide different levels of accuracy for these parameters. Analytical and semi-empirical methods are generally less accurate and are primarily used during the early design stages of classical airship configurations. CFD methods, in contrast, provide the highest accuracy and are typically employed during later stages of development, as well as for lighter-than-air vehicles with complex geometries, such as composite or combined configurations. The accuracy of aerodynamic parameter estimation directly affects the adequacy of 6-DoF airship flight simulations under different operating conditions, particularly in the presence of significant wind disturbances. Therefore, the development of rational methods for determining the aerodynamic characteristics of airships remains a highly relevant scientific and engineering problem.

The paper also proposes potential directions for the use of balloons and airships as means of countering strike UAVs for the protection of critical infrastructure.

Financing. This work was carried out in accordance with agreement No. 07/01-2026(7) dated 02.03.2026 between the NAS of Ukraine and the Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and the State Space Agency of Ukraine, which was concluded on the basis of the Order of the Presidium of the NAS of Ukraine dated 16.02.2026 No. 76. The research that led to the preparation of the manuscript was development of priority areas of scientific research» (CPCVK 6541230)

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Received on April 24, 2026;
approved on June 29, 2026;
published on July 2, 2026.