Multiple robots (robotic centers) and systems. Remote sensing and non-destructive testing

Роботизированные комплексы и системы.
Технологии дистанционного зондирования неразрушающего контроля

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RESEARCH ARTICLE

Calculation of the main operational characteristics of a tethered high-altitude ship-based system

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Abstract
Objectives. Currently, UAVs are actively used in many military and civilian fields such as object surveillance, telecommunications, radar, photography, video recording, and mapping, etc. The main disadvantage of autonomous UAVs is their limited operating time. The long-term operation of UAVs on ships can be ensured by tethered high-altitude systems in which the power supply of engines and equipment is provided from the onboard energy source through a thin cable tether. This paper aims to select and justify the appearance of such system, as well as to calculate the required performance characteristics.
Methods. The study used methods of systemic and functional analysis of tethered system parameters, as well as methods and models of the theory of relations and measurement.
Results. The issues of design and implementation of new generation tethered high-altitude ship-based systems were considered. A rational type of aerodynamic design for unmanned aerial vehicles was determined based on existing tethered platforms. The optimal architecture of the tethered system was defined and justified. The paper presents the appearance and solution for placement onboard the ship, and describes its operation. The main initial parameters for designing high-altitude systems such as take-off weight, optimal lift altitude, maximum power required for operation, structure of the energy transfer system, as well as deployment and lift time to the design altitude were selected and calculated.
Conclusions. The methodology for calculating the necessary characteristics described in the paper can be used for developing and evaluating tethered high-altitude systems. These systems are capable of performing a wide range of tasks, without requiring a separate storage and launch location, which is especially important in the ship environment. The system presented herein possesses significant advantages over well-known analogues.

Keywords: tethered high-altitude platform, unmanned aerial vehicle, power, energy transfer, ship, transport and launch container

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НАУЧНАЯ СТАТЬЯ

Расчет основных эксплуатационных характеристик привязной высотной системы корабельного базирования

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Резюме
Цели. Беспилотные летательные аппараты (БПЛА) активно применяются во многих военных и гражданских областях: мониторинг критических объектов, телекоммуникации, радиолокация, фото- и видеосъемка, картографирование и др. Основным недостатком автономных БПЛА является ограниченное время функционирования. Длительное функционирование БПЛА на кораблях могут обеспечить привязные высотные системы (ПВС), в которых электропитание двигателей и аппаратуры полезной нагрузки осуществляется от бортового источника энергии по тонкому кабель-тросу. Цель работы – выбор и обоснование облика ПВС, расчет необходимых эксплуатационных характеристик.
Методы. В работе используются методы системного и функционального анализа параметров привязной системы, методы и модели теории отношений и измерения.
Результаты. Рассмотрены вопросы проектирования и реализации нового поколения ПВС корабельного базирования. На основе существующих привязных платформ определен рациональный тип аэродинамической схемы БПЛА. Определена и обоснована оптимальная архитектура привязной системы, представлен ее облик и решение по размещению на корабле, а также описана ее работа. Выбраны и рассчитаны основные исходные параметры для проектирования высотных систем, такие как взлетная масса, оптимальная высота подъема, максимальная необходимая мощность для функционирования, структура системы передачи энергии, время развертывания и подъема на расчетную высоту.
Выводы. Представленная в статье методология расчета необходимых характеристик позволяет использовать ее для разработки и оценки ПВС. Данные системы способны выполнять различный спектр задач, при этом не требуя отдельного места хранения и запуска, что особенно актуально в корабельных условиях. Представленная система имеет значительные преимущества перед известными аналогами.

Ключевые слова: привязная высотная платформа, беспилотный аппарат, мощность, передача энергии, корабль, транспортно-пусковой контейнер

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INTRODUCTION

Today, multirotor unmanned aerial vehicles (UAVs) have become widespread and intensely developed. UAVs have many irrefutable advantages including simple and inexpensive designs in contrast to large aircraft systems, as well as safety, low maintenance, absence of the need for special launch sites, and efficiency. The main disadvantage of the UAV is low (limited) flight autonomy due to the insufficient battery capacity of UAVs equipped with electric motors [1].

Long-term UAV operation can be ensured by a continuous power supply using tethered high-altitude systems (THAS). In such systems, high power energy is transferred to UAV while the UAV is maintained at a certain altitude by means of a thin cable tether [2]. At the same time, THAS enables the precise landing of the UAV at the designated location. It can also be used in places with barriers (obstacles), e.g., on the deck of a ship.

In the Russian Navy (Navy), THAS is used for video surveillance, target designation, communication, and electronic warfare, etc. However, the mass use of THAS on ships is currently difficult due to the lack of specialized storage sites, as well as simple and reliable launch and landing systems [3].

DESIGN AND CALCULATION OF THAS PERFORMANCE CHARACTERISTICS

The following activities are required for the development of ship-based THAS:

- defining the operating architecture, appearance, and THAS storage and launch sites;
- calculating the basic tactical and operational characteristics;
- calculating the parameters of tolerance to external disturbances.

At the present time, the Navy is searching for the optimal placement of the THAS storage, take-off, and landing sites along with their operation and maintenance facilities on ships. In most cases, this is due to the need for a significant change in the external and internal architecture of the ship in order to find the necessary space [3]. This approach is unacceptable for a warship since it may cause significant changes in its operational and technical characteristics. Therefore, the solution to the problem of storing, launching, and landing THAS should be reduced to the need for searching for other ways using special means.

In architectural terms, advanced THAS is a system consisting of airborne (UAV) and shipborne modules connected to each other by a flexible link (cable tether) and placed in a standard transporter-launcher container (TLC) for vertical launching systems (VLS) located below the upper deck (Fig. 1).

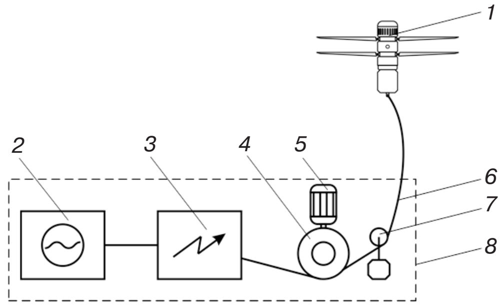


Fig. 1. Ship-based tethered high-altitude system: *1* air module (UAV), *2* alternating current source, *3* voltage converter and winch control system, *4* winch, *5* winch drive, *6* cable tether, *7* cable tether tension sensor, and *8* shipborne module

The unmanned aerial vehicle holds the payload on board at a given point above sea level. The UAV is mechanically linked to the shipborne module by a cable tether. The ship module includes an AC voltage source, voltage converter, winch control system, winch drive, and a cable tether tension sensor. The appearance of the THAS located in TLC is shown in Fig. 2.

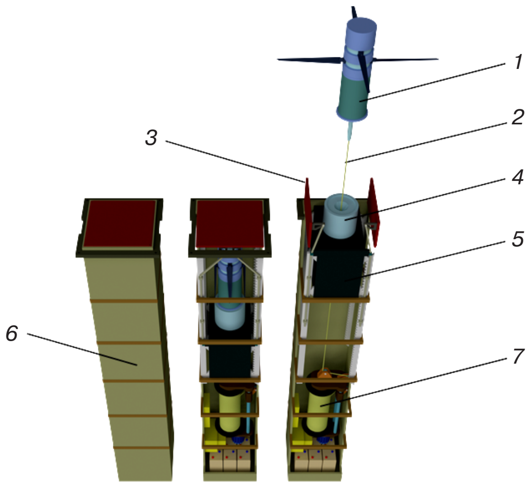


Fig. 2. THAS located in TLC: *1* UAV, *2* cable tether, *3* lid flaps, *4* cup, *5* pedestal, *6* TLC, and *7* winch

When selecting the type of UAV, its specific operating features should be taken into account [4] along with operating conditions. The UAV's dependence for spatial orientation on the force and direction of the wind load should be minimized. Therefore, three aerodynamic schemes can be used for THAS: single-rotor UAV with several steering devices (steering propellers) symmetrically located relative to the axis of the main rotor; coaxial; and a multi-rotor one with four or more propellers located symmetrically relative to the UAV center.

All types of UAV have their own advantages and disadvantages. However, despite the relative complexity of the design, a coaxial scheme is selected for THAS. Its heading orientation is slightly dependent on wind direction. This UAV type is simpler to store and launch from a container: a rational solution under given conditions.

The following are the main initial designed parameters when developing THAS:

- the UAV take-off weight, including the weight of UAV itself, payload weight, and cable tether weight;
- optimal UAV flying altitude;
- maximum power required for UAV operation;
- the system structure for transferring power to UAV;
- UAV deployment and lift time to the set altitude.

THAS operates as follows. In the storage base, the UAV is equipped with the payload required for specific missions. The TLC is loaded into VLS (Fig. 2). Prior to using the device, the VLS lid is opened. Then, the TLC lid flaps are opened using the drive. This is followed by lifting the cup which is rigidly fixed on the pedestal.

Once the pedestal is lifted to the highest position, the propellers of the UAV are started. They are driven by at least two electric motors powered through the cable tether. The UAV begins to rise vertically. The control system generates the voltage necessary for the winch drive which rotates, in order to unwind the cable tether connected to the UAV's pin via the tension sensor, roller system, and cable laying equipment. A tension sensor is required for maintaining a set tension force of the cable tether and preventing emergencies by generating signals for the control system. During operation (rising and hovering at a certain altitude), the UAV is supplied with high voltage from the control system through the cable tether, reduced by the onboard converter to the value required for operating the UAV with the payload installed on it.

After gaining altitude, the UAV is stabilized relative to the horizon and heading with the specified accuracy. It is maintained in this position during the entire operation. UAV stabilization during operation is carried out automatically by a system of sensors: gyroscope, accelerometer, barometric altimeter (altimeter), and three-component magnetometer. The control laws are formed using a microprocessor to stabilize heading, roll, and pitch, as well as to resist wind disturbances. The UAV drift due to wind or ship motion is compensated by the global navigation system receiver and accelerometers. The vertical movements caused by wave action are compensated by changing the length of the cable tether in response to signals from onboard sensors and the control system.

In the event of an emergency or a lack of power supply from the onboard source, the UAV is powered by batteries located in the bottom part of the TLC. In the case of a cable tether breakage, the UAV is provided with an automatic emergency landing mode using the onboard battery energy.

Landing is performed in the reverse sequence. In this case, the constant tension of the cable tether ensures UAV leveling over the cup. The deployment, take-off, landing, and rollback of the onboard tethered high-altitude system are performed automatically.

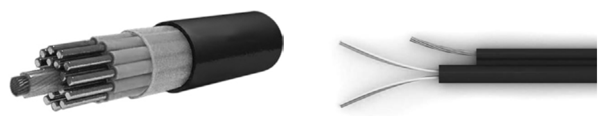
TAKE-OFF WEIGHT

In UAV design, an important parameter is the maximum take-off weight of the UAV. This means the UAV weight with the payload installed and the weight of the cable tether of the maximum possible length:

$$m_{\mathrm{TO}} = m_{\mathrm{UAV}} + m_{\mathrm{PL}} + m_{\mathrm{CT}} h, \tag{1}$$

where m_{UAV} is UAV weight, m_{PL} is the payload weight, m_{CT} is the cable tether weight per unit length, and h is UAV altitude.

In Eq. (1), the unknown quantity is the last summand dependent on the cable tether used and the UAV altitude. The cable tether may consist of either the cable with support tether or the cable attached to support tether separately (Fig. 3).



(a) (b)

Fig. 3. Cable tether versions: (a) CPVLS[1] power cable, (b) UTP[2] cable tether

The first version is preferable since it has a more compact and easy-to-use design. The cable tether production technology implies using the insulated power cable in its center, and the insulated wires with copper conductive conductors of round cross-section around it. The cable tether outer protective sheath consists of insulating material. Inside the cable outer sheath, there are voids filled with low density material which provide the system with crush resistance.

The main materials used in producing cable tether are copper, kevlar, fiber optics, and plastics. The cable weight per unit length is determined by the following equation:

$$m_{\mathrm{CT}} = \rho_{\mathrm{K}} S_{\mathrm{Teth}} + \rho_{\mathrm{Cu}} S_{\mathrm{Cu}} u_{\mathrm{Cu}} n + \\ + \rho_{\mathrm{Ins}} S_{\mathrm{Ins}} + \rho_{\mathrm{Sh}} S_{\mathrm{Sh}} + \rho_{\mathrm{Fill}} S_{\mathrm{Fill}} + \rho_{\mathrm{OF}} S_{\mathrm{OF}}, \tag{2}$$

where ρ_{K}, ρ_{Cu}, ρ_{Ins}, ρ_{Sh}, ρ_{Fill}, and ρ_{OF} are densities of kevlar, copper, insulation, sheath, filling material,

[1] C is control cable, P is polyethylene core insulation, V is polyvinyl chloride plastic sheath, L is lifting cable, and S means with load-carrying tether made of synthetic threads.

[2] UTP is the unshielded twisted pair.

and optical fiber, respectively; u_{Cu} is the coefficient accounting for twisting of wires in the conductive core; S_{Teth}, S_{Cu}, S_{Ins}, S_{Sh}, S_{Fill}, and S_{OF} are cross-sectional areas of the tether, copper conductor, insulation, sheath, filling, and optical fiber, respectively; and n is number of copper conductors.

For further calculations, the following constraints are assumed:

- the optical fiber is homogeneous over the entire cross-section;
- the outer sheath has a circular cross-section;
- thickness and insulation material of all cores and cable are the same;
- all cores have the same cross-section.

A simplified version of the cross-section of a cable tether with two copper conductors and optical fiber is shown in Fig. 4.

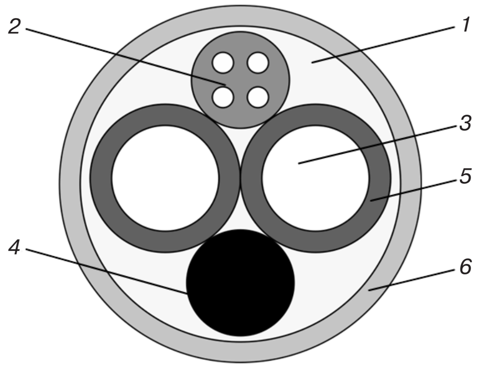


Fig. 4. Cross section of a cable tether: *1* filling material, *2* optical fiber, *3* copper core, *4* kevlar tether, *5* insulation, and *6* sheath

The insulation area S_{Ins} is calculated by means of the following formula:

$$S_{Ins} = 2\pi k_{Ins}(r_{Cond} - k_{Ins}/2)(n+1), \quad (3)$$

where k_{Ins} is the insulation thickness, r_{Cond} is the conductor radius.

The area of the sheath is determined as follows:

$$S_{Sh} = 2\pi k_{Sh}(r_{CT} - k_{Sh}/2), \quad (4)$$

where k_{Sh} is thickness of the sheath, r_{CT} is radius of the cable tether.

The radius of the considered cable tether is determined by means of the following formula:

$$r_{CT} = k_{Sh} + 3k_{Ins} + 2r_{Cu} + r_{Teth}, \quad (5)$$

where r_{Teth} is the tether radius, r_{Cu} is the copper core radius.

The cross-section of the filling material has a complex shape, so its area is determined by means of the following expression:

$$\begin{aligned} S_{Fill} = {} & \pi r_{CT}^2 - \pi(r_{Teth}^2 u_{Teth} + r_{Cu}^2 u_{Cu} n + \\ & + 2k_{Ins}(r_{Cond} - k_{Ins}/2)(n+1) + \\ & + r_{OF}^2 + 2k_{Sh}(r_{CT} - k_{Sh}/2)), \end{aligned} \quad (6)$$

where r_{OF} is the optical fiber radius.

After transforming expression (6), the following is obtained:

$$\begin{aligned} S_{Fill} = {} & \pi((r_{CT} - k_{Sh})^2 - \\ & - ((r_{Teth} + k_{Ins})^2 u_{Teth} + r_{Cond}^2 u_{Cu} n + r_{OF}^2)). \end{aligned} \quad (7)$$

By substituting equations (3), (4), and (7) into (2), we obtain the following:

$$\begin{aligned} m_{CT} = {} & \rho_K \pi r_{Teth}^2 + \\ & + \rho_{Cu} \pi r_{Cu}^2 u_{Cu} n + \\ & + \rho_{Ins} 2\pi k_{Ins}(r_{Cond} - k_{Ins}/2)(n+1) + \\ & + \rho_{Sh} 2\pi k_{Sh}(r_{CT} - k_{Sh}/2) + \\ & + \rho_{Fill}(\pi((r_{CT} - k_{Sh})^2 - \\ & - ((r_{Teth} + k_{Ins})^2 u_{Teth} + r_{Cond}^2 u_{Cu} n + r_{OF}^2))) + \\ & + \rho_{OF} \pi r_{OF}^2. \end{aligned} \quad (8)$$

Assuming r_{Teth} = 0.0015 m, r_{Cu} = 0.00075 m, r_{OF} = 0.001 m, r_{Cond} = 0.00155 m, and $r_{Ins} = k_{Sh}$ = 0.0008 m, we obtain m_{CT} = 0.09 kg. Thus, the UAV weight with cable tether increases by 9 kg at an altitude of 100 m.

OPTIMAL UAV LIFT ALTITUDE

The UAV lift altitude directly affects the operating efficiency of THAS suspended equipment: the higher the altitude, the greater the view.

Maximum radar range is limited by the line of sight to the target whose value (in km) is determined by the following commonly known formula (derived from the basic radar equation [5]):

$$L_{max} \approx 4.12\left(\sqrt{h_a} + \sqrt{h_{Tgt}}\right), \quad (9)$$

where h_a is the antenna height (UAV lift altitude), h_{Tgt} is the target height.

At target height h_{Tgt} = 0 (e.g., small-sized surface target) and target surveillance from the upper deck of the ship ($h_a \approx 10$ m), the radar track acquisition range is $L_{max} \approx 13$ km. However, when elevating the means of surveillance to $h_a \approx 100$ m, the maximum range increases more than 3 times up to $L_{max} \approx 41$ km. Dependence of the horizon visibility range on the surveillance height is presented in Fig. 5.

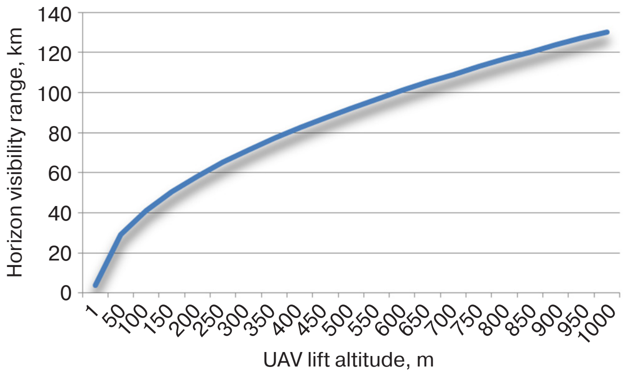


Fig. 5. Dependence of horizon visibility range on surveillance height

However, increasing UAV lift altitude results in increasing its power consumption and wind speed [6]. Comparing the simulation results of THAS application conditions [7, 8], it can be concluded that the rational lift altitude is about 100 m.

MAXIMUM POWER REQUIRED FOR UAV OPERATION

The suspended UAV and the forces acting on it are shown in Fig. 6, where F_g is gravity force, F_t is thrust force of UAV engines, F_{WR} is wind resistance force, and F_{CT} is cable tether tension force.

The modulus of all forces acting on UAV is calculated using the following formula [6]:

$$\left|\mathbf{F}_t\right| = \sqrt{(\left|\mathbf{F}_g\right| + \left|\mathbf{F}_{CT}\right|\cos\alpha)^2 + (\left|\mathbf{F}_{WR}\right| + \left|\mathbf{F}_{CT}\right|\sin\alpha)^2}, \quad (10)$$

where α is the vector angle of the cable tether tension force to the vertical.

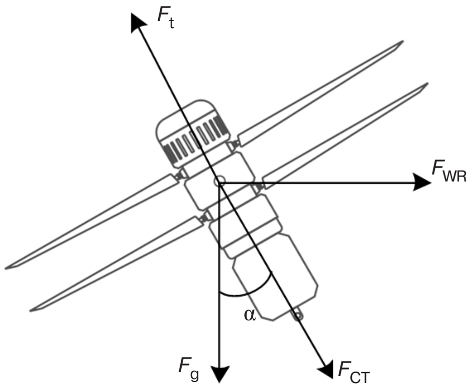


Fig. 6. UAV with forces acting on it

The gravity force is determined by the UAV take-off weight, as follows:

$$F_g = m_{UAV}g + m_{PL}g + m_{CT}g, \quad (11)$$

where g is gravity acceleration.

The wind resistance force is determined by the following equation[3]:

$$F_{WR} = C\rho S v^2 = CqS, \quad (12)$$

where C is the aerodynamic coefficient, S is the UAV area projection onto the direction perpendicular to the oncoming flow, v is oncoming air flow velocity, ρ is the air density, and q is the wind pressure.

As follows from (12), the UAV geometric characteristics, the velocity head, and the aerodynamic coefficient need to be known, in order to determine the wind effect. The known values are geometric characteristics and aerodynamic coefficient.

We consider aerodynamic loads under wind effect as operating and limiting. Under the operating wind effect, the UAV may be used without limiting conditions. Under the limiting wind effect, the UAV should retain its strength and stability, as well as provide other performance requirements.

Specified parameters for operational wind effect are the estimated maximum value of the average (with a two-minute averaging period) wind speed at an altitude of 10 m from the ground surface and the minimum ambient temperature at which UAV operation is allowed.

The estimated velocity head at operating effect is determined by the following equation:

$$q_{est} = \frac{\rho v_{est}^2}{2}, \quad (13)$$

where v_{est} is the estimated average wind speed under operational impact.

When calculating the wind load on a moving ship, its speed should be taken into account whenever it exceeds $0.025v_{est}$. In this case, for a given average wind speed, the estimated velocity head when traveling against the wind is determined by means of the following equation:

$$q_{est} = \frac{\rho(v_{est} + v_{max})^2}{2}, \quad (14)$$

where v_{max} is the maximum speed of the ship.

Based on the limiting value of the standard average velocity head q_{LV}, the estimated velocity head for the limiting wind effect is determined as follows:

$$q_{est} = q_{LV}\mu, \quad (15)$$

where μ is the overload factor taken equal to 1.0–1.3.

[3] OST 92–9249–80. Industry standard. *Units of special purpose. Calculation methodology for wind loads*. 1980 (in Russ.).

The coefficient C_i depends on angle α, wind direction, and UAV profile.[4]

The engine power required to hold the UAV at a given point, after determining the resultant force modulus, is calculated using the following equation:

$$P = \frac{|\mathbf{F}_\mathrm{t}|}{k \times \mathrm{g}}, \quad (16)$$

where $|\mathbf{F}_\mathrm{t}|/\mathrm{g}$ is the total thrust of the UAV engines; k is the efficiency factor of the propeller group which characterizes the ratio of the engine total thrust to its power.

As is known from the practical implementation of THAS, and propeller group selection, k = 10 kg/kW and higher is considered a good value for the efficiency factor. This implies the ability to lift 10 kg of load for every kilowatt of energy expended. The efficiency factor depends largely on the engine type and traction propeller characteristics. For THAS, as the altitude rises, the load weight increases (due to the increasing tension force of the cable tether). Consequently, the propeller motor group efficiency decreases.[5]

The calculation of the tension force (F_CT) acting on THAS due to the cable tether is described in [9]. It represents a differential equation system: one being a linear differential equation of the first order; while the other two being nonlinear differential equations of the second order. It should be noted that the system of differential equations obtained coincides with the flexible thread position equation [10] for a tethered flying object:

$$\begin{cases} \dfrac{dF_\mathrm{CT}}{dz} - \rho_\mathrm{CT}\mathrm{g} = 0, \\ F_\mathrm{CT}\dfrac{d^2x}{dz^2} + \rho_\mathrm{CT}\mathrm{g}\dfrac{dx}{dz}\left(1+\left(\dfrac{dx}{dz}\right)^2+\left(\dfrac{dy}{dz}\right)^2\right) + \\ +A\sqrt{v_x^2(z)+v_y^2(z)+\left(v_x(z)\dfrac{dy}{dz}-v_y(z)\dfrac{dx}{dz}\right)^2} \times \\ \times v_x(z)\sqrt{1+\left(\dfrac{dx}{dz}\right)^2+\left(\dfrac{dy}{dz}\right)^2} = 0, \\ F_\mathrm{CT}\dfrac{d^2y}{dz^2} + \rho_\mathrm{CT}\mathrm{g}\dfrac{dy}{dz}\left(1+\left(\dfrac{dx}{dz}\right)^2+\left(\dfrac{dy}{dz}\right)^2\right) + \\ +A\sqrt{v_x^2(z)+v_y^2(z)+\left(v_x(z)\dfrac{dy}{dz}-v_y(z)\dfrac{dx}{dz}\right)^2} \times \\ \times v_y(z)\sqrt{1+\left(\dfrac{dx}{dz}\right)^2+\left(\dfrac{dy}{dz}\right)^2} = 0, \end{cases} \quad (17)$$

where A is the aerodynamic drag factor; ρ_CT is the cable tether linear density; x, y, z is the rectangular coordinate system; v_x, v_y, v_z are the projections of wind velocity onto corresponding axes of the rectangular coordinate system.

The problem under consideration is complicated by the need to resolve not the Cauchy problem but the boundary problem, when the conditions are set at different values for argument z [11].

Given (10), (11), (16), and (17), the required power for operating THAS is defined as follows:

$$P = \frac{\sqrt{(m_\mathrm{UAV}\mathrm{g} + m_\mathrm{PL}\mathrm{g} + |\mathbf{F}_\mathrm{CT}|\sin\alpha)^2 + (|\mathbf{F}_\mathrm{WR}| + |\mathbf{F}_\mathrm{CT}|\cos\alpha)^2}}{k \times \mathrm{g}}. \quad (18)$$

The work of A.M. Shirvanyan[6] presents the calculation of the required power for operating THAS of 25 kg and 35 kg in weight at an altitude of 75 m under tension force F_CT = 10 H and 30 H (Fig. 7). From this, it can be concluded that a high wind speed and ship motion have a significant effect on the required power. When wind speed (and/or ship motion) increases, slope angle α of the cable-tether tension force action F_CT on THAS increases, thus increasing the horizontal component of the tension force. In addition, changing the cable tether tension force by the winch will change its profile and length significantly.

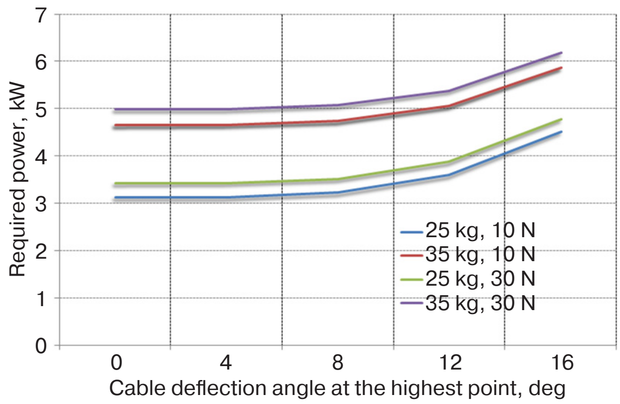


Fig. 7. Dependence of THAS required power on the wind speed at different weight and tension force of the cable tether

For the cable winch drive control system, a balance needs to be found between the tension force of the cable tether at the winch and the UAV power consumption. Weak winch tension may trigger a large cable tether release which is unsafe in a shipboard environment.

[4] Albisser M. *Identification of Aerodynamic Coefficients from Free-Flight Data*. Université de Lorraine, Nancy, France, Ph.D. Thesis, 2015.

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Strong winch tension makes the cable profile nearly vertical. However, this significantly increases the UAV power required for operating.

The findings are significant for estimating the maximum payload weight and the required electrical power transferred from the ship to the UAV under conditions of wind loads and ship motion, as well as for designing the THAS positioning control system.

THE SYSTEM STRUCTURE FOR TRANSFERRING POWER TO UAV

The efficient UAV operation requires a high power supply. Currently, there are effective UAV power supply systems based on high-frequency direct or alternating current (AC). A large number of studies [12–15] deal with selecting the type of current supply for suspended systems. In the case of an AC power supply, a relatively high efficiency and smaller conductor cross-sectional area can be obtained, when compared to direct current (DC). However, in a long supply line, wave processes consisting in the occurrence of a reflected wave inevitably occur. This results in an increase in voltage on some parts of the cable-rope. In the coiled state (around the winch drum), the cable tether reel represents an inductive resistance, which also prevents the transmission of alternating current. At the same time, power transfer at industrial frequency results in the need for conversion, thus reducing the payload weight.

For the same level of power, the cross-sectional area of the conductor decreases with the increasing supply voltage. Thus high voltage needs to be transmitted through the cable tether for the UAV power supply. The structure of the power supply circuit is shown in Fig. 8.

The maximum power transmitted through the cable tether depends on the type of current. In order to calculate the maximum transmitted power, the wire diameter (cross-sectional area), current density, interwire voltage (for DC), and wave impedance (for AC) need to be determined.

The DC power is determined by means of the following equation:

$$P_{\mathrm{DC}} = IU = \pi \frac{d_{\mathrm{Cu}}^2}{4} JU, \tag{19}$$

where I is the current strength, d_{Cu} is the diameter of the copper conductor, J is the current density, and U is the interwire voltage.

Losses per unit length in wires are determined by means of the following equation [16]:

$$\Delta_{\mathrm{DC}} = 2S_{\mathrm{Cu}} J^2 \sigma, \tag{20}$$

where σ stands for the conducting material conductivity.

When building an AC power system, reflected waves transfer energy from the point of the line connection to the load backward to the power source. Equality of the line wave impedance to the line load impedance is the condition for maximum AC power transfer efficiency. The maximum transmitted power is determined as follows:

$$P_{\mathrm{AC}} = I^2 \tilde{R} = I^2 \frac{120}{\sqrt{\varepsilon}} \ln \frac{l_{\mathrm{Cu}}}{r_{\mathrm{Cu}}}, \tag{21}$$

where $\tilde{R}$ is the wave impedance for a two-conductor line, l_{Cu} is the distance between centers of two

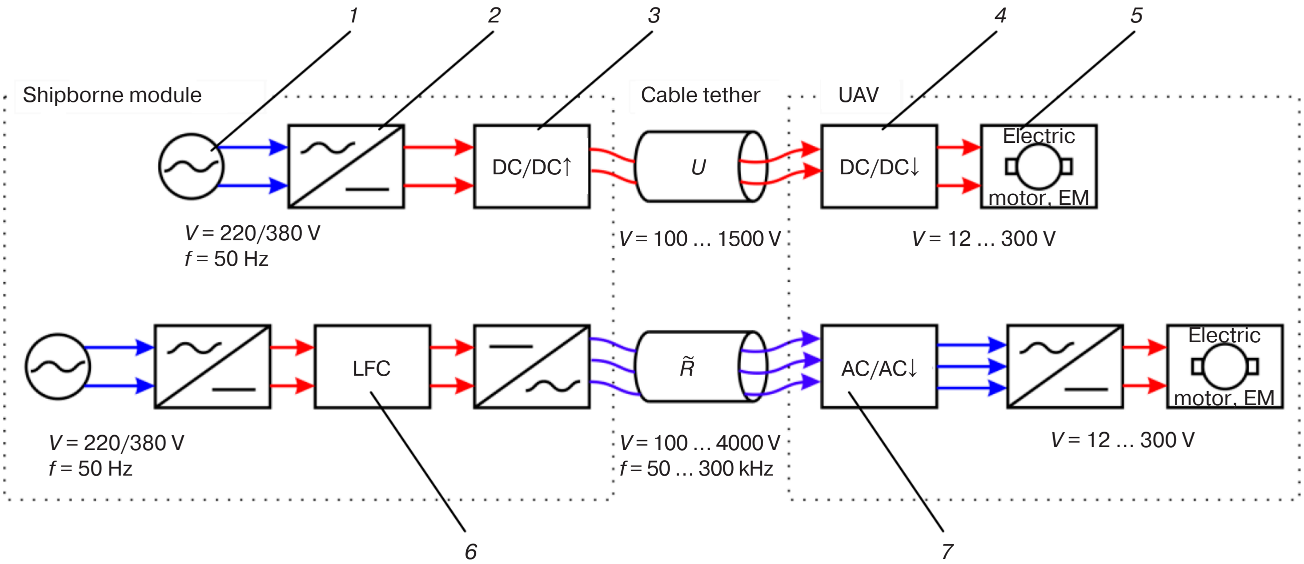

Fig. 8. THAS power circuit structure: *1* AC voltage source, *2* rectifier, *3* direct current boost converter, *4* DC-DC voltage converter, *5* UAV and payload consumer, *6* low frequency converter, *7* alternating current buck converter. *V* is a voltage, *f* is a frequency

conductors, ε is the dielectric permeability of the medium between conductors.

The AC power losses are determined by means of the following equations:

$$\Delta_{AC} = 2S_{Cu}\sigma(K_s J)^2, \quad (22)$$

where K_s is the section utilization factor.

Thus, a comparison of (20) and (22) shows that power losses in AC transmission are lower than those in DC transmission due to the skin effect. When using a cable with d_{Cu} > 6 mm, the maximum possible AC power increases significantly. For example, at d_{Cu} = 8 mm and 1200 V voltage, it is possible to transmit 48 kW DC, whereas 135 kW AC.

Nguen et al. [17] determines that a slight increase in the radius of the conductive core r_{Cu} results in a large increase in the transmitted power, reducing the share of the cost required to lift and hold the cable tether. In the case of a smaller conductive core radius, the maximum power depends insignificantly on the type of current. Thus, the transmission of high power (over 14 kW) is preferable to AC, while DC is more appropriate for lower power.

DEPLOYMENT TIME AND UAV LIFTING TO THE SET ALTITUDE

In addition to its obvious advantages, the placement of the THAS in TLC has a significant disadvantage. The transporter-launcher container is loaded into a vertical launcher which contains certain means of destruction of various types and purposes. Since there may be THAS or UAV cable tethers on their trajectory, the operation of deployed THAS prevents the use of these means either partially or completely. Therefore, the calculation of deployment (redeployment) time is of great importance when operating THAS on Navy ships. The deployment time is calculated using the following equation:

$$t_{Dep} = t_{ad} + h / v_{da}, \quad (23)$$

where t_{ad} is the ascent (descent) time of the platform with UAV in TLC, v_{da} is the speed of UAV descent (ascent).

At t_{ad} = 5 s and v_{da} = 4 m/s, the redeployment time from an altitude of 100 m amounts to 30 s.

For comparison, the tethered ETOP UAV (Israel Aerospace Industries, Israel) with 20 kg maximum payload and 100 m altitude has a comparable deployment time [17].

CONCLUSIONS

Implementing the principles of THAS construction under consideration in this study allows the creation of a complex capable of performing various tasks with a high level of efficiency. The proposed THAS has significant advantages over known platforms. They include: container storage and launch, high-power energy transmission system via low-section cable tether (low weight per unit length), and stabilization of UAV with payload by altitude. At the same time, the advanced THAS provides payload lifting to an altitude of 100 m with a long operational life, only limited by THAS reliability characteristics.

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