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Article

Study and Analysis of the Relationship between Longitudinal Moment Coefficient and Angle of Attack or Lift Coefficient based on the Stability and Controllability of the ekranoplan

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Abstract: The ekranoplan, as a special type of vessel, combines the performance of an aircraft and a ship. It boasts high speed, low radar visibility, good maneuverability, excellent amphibious capabilities, and a unique feature that sets it apart from other vessels: it is immune to torpedo and mine attacks. This article aims to introduce the main component design of the ekranoplan, the composition of its power system, and analyze its stability and controllability. Through graphical analysis, the relationship between the longitudinal moment coefficient, attack angle, and lift coefficient of an aircraft was studied. The results indicate that ensuring stability for the ekranoplan is more challenging compared to an aircraft. The paper provides a good basis for subsequent seakeeping experiments on ground-effect winged vehicles, which is of great significance.

Keywords: ekranoplan, design, military.

1. Introduction

The ekranoplan, officially classified in the Soviet Union as a "ship on a dynamic air cushion," is a high-speed transportation vehicle that flies within the aerodynamic screen, at a relatively low altitude (a few meters) above the surface of water, land, snow or ice.

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Compared to an airplane of similar weight and speed, the ekranoplan has a much smaller wing area. According to the International Maritime Organization (IMO) classification, ekranoplans are considered as marine vessels [1].

As defined in the "Temporary Guidelines on Ekranoplan Safety" adopted by the IMO, the ekranoplan is a multi-mode vessel that, in its primary operational mode, flies utilizing the "ground effect" over a water or other surface, without constant contact with it. It is primarily supported in the air by aerodynamic lift generated on the airfoil (wings), body, or their parts that are designed to utilize the "ground effect" [2].

Ekranoplans are capable of operating on various routes, including those inaccessible to conventional ships. Besides having higher hydrodynamic qualities and seafaring capabilities compared to other high-speed vessels, ekranoplans almost always possess amphibious properties [3]. In addition to gliding over water surfaces, they can also move over solid surfaces such as land, snow, and ice, and can be based on them. Therefore, the ekranoplan combines the best qualities of a ship and an airplane.

This article mainly introduces the operating principle of a ground effect vehicle called a ekranoplan craft. It discusses the concept of ground effect and provides insights into the design of the ekranoplan crafts, including the wing structure, propulsion system, internal cabin partitioning, and mechanical devices. Furthermore, the article analyzes the stability and controllability aspects of the ekranoplan crafts.

At present, the development technology of small and medium-sized Ekranoplan is mature, but the design of large ekranoplan has been stagnant due to the high cost of construction and the worse weather adaptability of large Ekranoplan, and it is one of the main tasks of the developers of the special ship program to put large Ekranoplan into construction and service.

2. Ground effect

Essentially, the ground effect is essentially an air cushion formed by the compression of air not with specialized devices, but with an approaching airflow. In other words, The "wing" of such vehicles generates lift not only by the lower pressure above the upper surface (as in "conventional" aircraft), but also by the increased pressure below the lower surface, which can only be created at very low altitudes (from a few centimeters to a few meters). This altitude is comparable to the mean aerodynamic chord (MAC) length of the wing. Therefore, efforts are made to design the wing of the ekranoplan with a small aspect ratio.

The ground effect is associated with the fact that the disturbances (pressure increase) from the wing reach the ground (water), reflect and manage to reach the wing. Thus, the pressure increase below the wing becomes significant. The propagation speed of the pressure wave, of course, is equal to the speed of sound. The larger the MAC of the wing, the lower the flight speed and altitude, the higher the ground effect. For example, the maximum flight range of the "Ivolga" ekranoplan at an altitude of 0.8 m is 1150 km, while at an altitude of 0.3 m with the same payload, it is already 1480 km. Traditionally, at flight speeds near the ground, the height of ground effect is considered to be half the wing chord. This gives a height of about one meter. However, for sufficiently large ekranoplans, the flight height "in the ground effect" can reach 10 meters or more. The center of pressure (the overall point of force application) of the ground effect is located closer to the rear edge, while the center of pressure of "conventional" lift is closer to the front edge, so the greater the contribution of the ground effect to the overall lift, the further back the center of pressure shifts [4]. This leads to balancing problems. Changing the altitude affects the balance, as does changing the speed. Roll causes diagonal displacement of the center of pressure. Therefore, controlling the ekranoplan requires specific skills.

3. Ekranoplan Designs

There are two major schools of thought when it comes to the ekranoplan designs: the Soviet school (led by Rostislav Alexeev) with a straight wing configuration (Figure. 1) [5], and the Western school (led by Alexander Lippisch) with a triangular wing configuration (Figure. 2) [5] featuring a pronounced reverse sweep and reverse dihedral. Alexeev's design requires more work on stabilization but allows for higher speeds and the ability to operate in aircraft mode. Lippisch's design incorporates measures to reduce excessive stability (wing with reverse sweep and reverse dihedral), which helps to mitigate the balancing issues of the ekranoplan operating within small dimensions and at lower speeds.

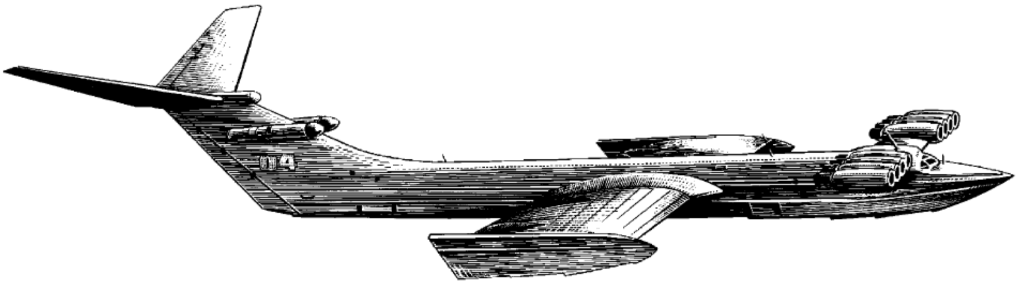

Figure. 1. The Caspian Sea Monster with straight wing [5]**.**

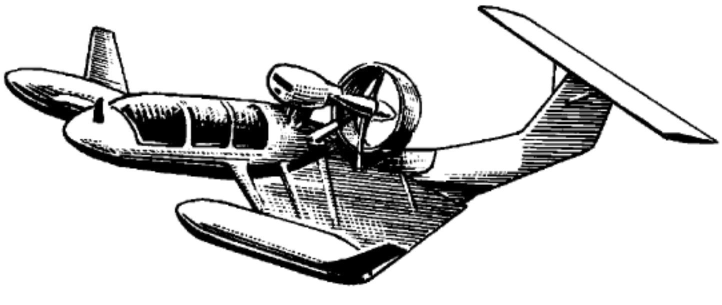

Figure. 2. Lippisch X-114 with delta wing [5]**.**

The third proposed design is the tandem scheme by G. Jörg. However, despite its advantages such as automatic stabilization, it has not gained many followers yet [3].

The concept of the ground effect is also employed by vessels with dynamic air cushions. Unlike ekranoplans, these vessels fly at even lower altitudes. However, compared to vessels with underwater wings and wing-in-ground effect vehicles, they can achieve higher speeds with lower energy consumption.

4. General structure and purpose of individual parts of the ekranoplan

4.1. Main elements of the ekranoplan

Figure 3 [6] shows the main parts of the ekranoplan. The fuselage similar to an airplane, is designed to accommodate the payload, crew, main devices, and systems of the ekranoplan, and also serves as a link connecting all the components of the aircraft's structure. Additionally, in classical ekranoplan layouts, the fuselage solves issues related to buoyancy, seakeeping, stability, and unsinkability. In such cases, the lower part of the fuselage is designed based on the seaplane scheme, meaning it has a stepped, keel-shaped bottom, which reduces resistance during takeoff and landing modes, as well as in the event of water contact during cruising mode.

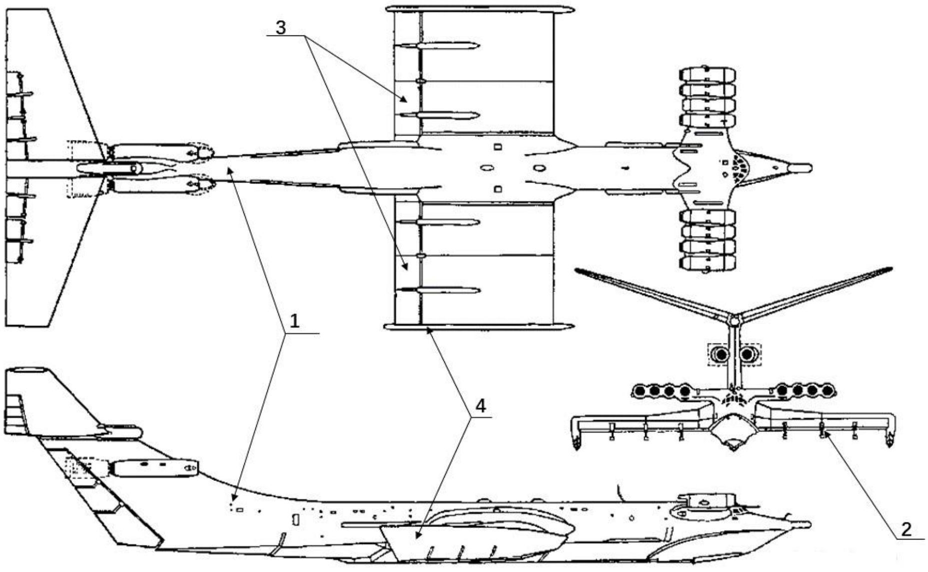

Figure. 3. Main parts of the ekranoplan: 1-fuselage; 2- lifting wing; 3- sectional flaps; 4- end plates [6].

To generate lift, the ekranoplan utilizes a lifting wing similar to an aircraft. The wing typically has a low aspect ratio Along with sectional flaps and end plates.

$$\lambda = \frac{l^2}{\mathrm{Sw}} \leq 3.5 \tag{1}$$

l - Wing spread

S_w - Wing area

The sectional flaps are mainly used during takeoff and landing, where the ekranoplan may come into contact with water or uneven surfaces. The sectional flaps also enhance safety in case of drive system failure. In addition to their traditional aircraft functions, the flaps of the ekranoplan are used for speed and altitude control during the ground effect flight. The area of the ekranoplan flaps can be significant, up to 15-20% of the wing area, with deflection angles (known for certain machines) ranging from -100 to + 450 degrees [7].

The end plates are widely employed on ekranoplans to increase lift and reduce induced drag by minimizing airflow from the high-pressure area under the wing to the low-pressure area above it. The lower surfaces of the end plates are typically designed as streamlined bodies with fillets. The use of end plates on ekranoplans is justified due to the significantly higher overpressure under the wing compared to an aircraft. Therefore, a chamber is formed under the lifting wing during takeoff and landing, which is bounded by the end plates and flaps. This chamber is utilized to create an air cushion by directing airflow into it from the leading edge of the wing (via engines, propellers, or fans).

4.2 Wing Configuration of the ekranoplan

The wing configuration of the ekranoplan, similar to an aircraft, is designed to address stability and controllability requirements. The horizontal stabilizer (HS) of the ekranoplan is typically installed with a longer arm and at a significant height relative to the wing. Additionally, the relative dimensions of the horizontal stabilizer, such as the span and area, greatly exceed the average values of these dimensions on an aircraft. In the early operational ekranoplanes developed under the guidance of R.E. Alexeev, the span of the HS was comparable to that of the main wing, and the area reached up to half the wing area [8]. Typically a horizontal stabilizer with high sweep was used, effectively increasing the center of pressure arm of the HS relative to the center of mass of the vehicle. All of this is connected to the specific features of the ekranoplan aerodynamics, particularly in terms of ensuring longitudinal stability and controllability , as show in Figure.4.

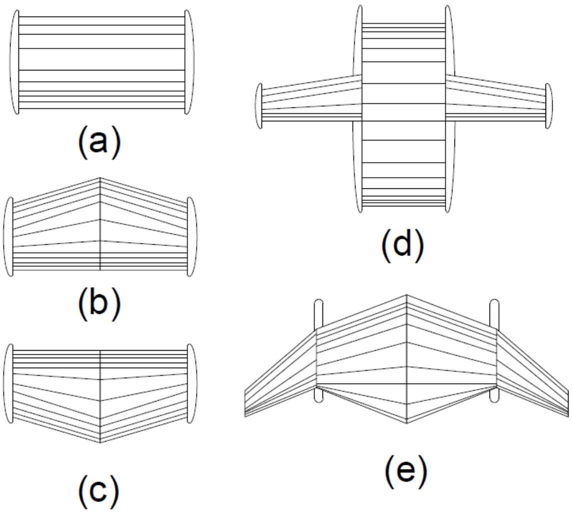

Figure. 4. Possible wing configurations in a plan view: a - rectangular; b - trapezoidal; c - with reverse sweep; d,e - compound wing.

The vertical stabilizer (VS) of the ekranoplan is responsible for lateral stability and control. Similar to the horizontal stabilizer, the VS differs from that of an airplane in terms of larger surface area and sweep, driven by the need for maximum outboard extension of the horizontal stabilizer towards the tail. The plan view shape of the VS may vary depending on the aerodynamic configuration of the vehicle.To balance and control the ekranoplan, it employs control surfaces such as the elevator and flaps (in the longitudinal plane) and the rudder and ailerons (in the lateral plane).

4.3 Powerplant of the Ekranoplan

The powerplant of the ekranoplan must ensure the vehicle's takeoff, including from a rough water surface, as well as its flight near the screen with maximum range and other characteristics specific to a particular ekranoplan (amphibious qualities, short-duration flight away from the screen, etc.).

There are two fundamental approaches to forming the powerplant of the ekranoplan. The first approach involves a separate powerplant configuration: a group of engines specifically for takeoff and another group of engines for the main flight mode near the screen. In this case, the nose engines are intended to operate only during takeoff with the help of an augmentor, thus they are called starter engines [9]. For the main flight mode, a highly efficient aft engine is used, which is referred to as the cruise engine. This principle is employed in the powerplant configuration of the "Orlyonok" ekranoplan (Figure. 5, a). For specific flight modes (flight in the overload configuration, flight in large screen or off-screen modes), the starter engines can be connected to the cruise engine (at zero deflection angle of the nozzles).

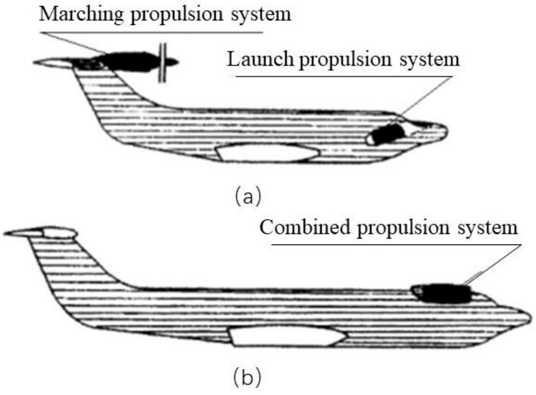

Figure. 5. Powerplant for the ekranoplan: a - separate; b – unified [9].

The second approach involves integrating the power unit of the ekranoplan into a unified system. This type of configuration is used in the "Lun" ekranoplan (Figure. 5, b). In this case, all the engines installed on a dedicated pylon in front of the lifting wing are used both for takeoff and cruising.The first advantage of this approach is improving the economic efficiency of the ekranoplan, while the second advantage is enhancing its sea-going capabilities and operational qualities.

4.4 Comparison of various aerohydrodynamic ekranoplan configurations

The aerohydrodynamic configuration (AHC)(Figure.6) of the ekranoplan refers to the combination of its external shapes, sizes, and the spatial arrangement of its parts that ensure the necessary aerodynamic characteristics [10]. In addition to the elements typically found on an airplane, the AHC of the ekranoplan may include engine pylons, fins, air cushion limiting screens, various types of antennas, weaponry, and so on. These elements undoubtedly create additional resistance, which negatively affects the aerodynamic qualities of the vehicle.

The main types of AHC for ekranoplans are: "tandem," "airplane-like," "flying wing," and "compound wing." The "tandem" configuration was studied by R.E. Alexeyev in 1959. An experimental vehicle with a takeoff mass of about 3 tons and an engine thrust of 900 kgf was built. The ekranoplan reached a speed of about 200 km/h and demonstrated satisfactory stability and controllability near the cushion [10]. This configuration exhibits high sensitivity to the air cushion as both lifting surfaces are within its influence zone. However, it requires high takeoff and landing speeds, which is a drawback of this AHC. The "tandem" configuration cannot implement features like wing-blowing for takeoff and landing. Nowadays, the "tandem" configuration is rarely used in ekranoplan designs.

The AHC airplane configuration has gained wider recognition and has been implemented in ekranoplans such as the "Orlenok," "Lun," and "KM," which were also developed at R.E. Alexeev's Design Bureau. These ekranoplans boast high speeds of up to 500 km/h, the ability to navigate through waves as high as 3 meters, and a range of up to 2000 km [10].

The "flying wing" design is ideal from an aerodynamic perspective but falls short in terms of navigability and stability. Currently, many developments in ekranoplan construction employ the "composite wing" AHC. These aircraft, designed according to this scheme, are referred to as second-generation ekranoplans. The lifting wing of these machines is divided into two functional parts. The center section, with a low aspect ratio, maximizes the ground effect, while the outboard sections provide high aerodynamic efficiency and ekranoplan stability.

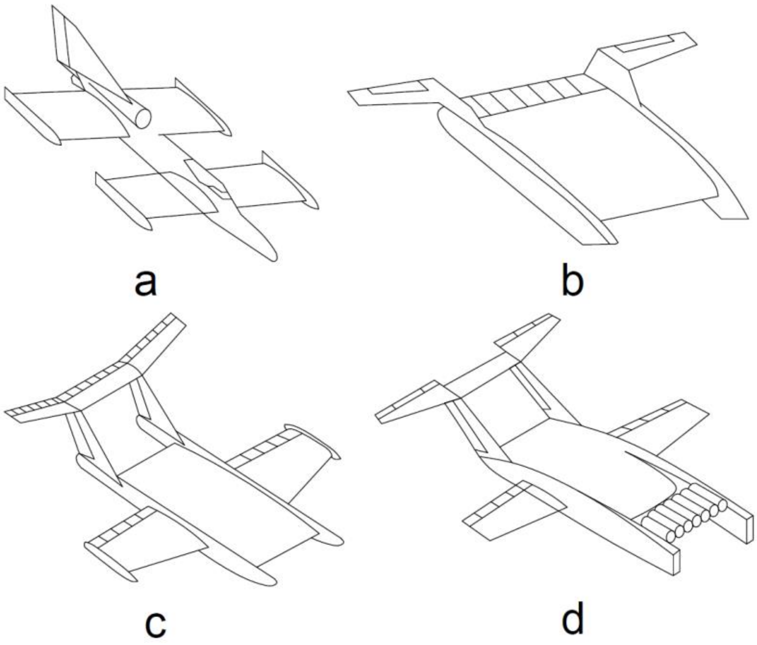

Figure. 6 AHC configurations of the ekranoplan: a - tandem; b - flying wing; c - composite wing; d - composite wing with blown air.

5.Stability and controllability of the ekranoplan

The stability of the ekranoplan refers to its ability to autonomously maintain a desired mode of motion, without the involvement of the crew, in case of deviations caused by various disturbances - returning to the original mode once the disturbances cease.The ekranoplan is considered stable if, during motion, it strives to maintain the original mode of motion despite the influence of various disturbances [11]. It is considered unstable if it deviates from the original mode of motion under these conditions, and if the deviation from the original mode increases over time after the disturbances cease.

The ekranoplan operates in three fundamental modes of motion: waterborne, takeoff and landing, and flight. Therefore, for each of these modes, stability and controllability are determined using calculation methods and experimental evaluations specific to that mode.

According to the general theory of stability, the stability of the ekranoplan is divided into static and dynamic stability.Static stability of the ekranoplan is determined by the direction of the moment created by its aerodynamic forces when the ekranoplan deviates from its equilibrium position. If this moment is directed towards the original equilibrium position, the ekranoplan is statically stable. If it is directed towards further increasing the initial deviation, the ekranoplan is statically unstable [12].The dynamic stability of the ekranoplan is determined by the nature of its perturbed motion. If the perturbed motion of the ekranoplan diminishes after the cessation of disturbances, the ekranoplan is dynamically stable. If it continues to develop, it is unstable.

Under the term "controllability" of the ekranoplan, we understand its ability to respond to changes in the parameters of motion through control actions of the crew using control surfaces, engine operation, and the configuration of the ekranoplan [7].

Stability and controllability of the ekranoplan are closely interrelated. The control of the ekranoplan is easier and more precise when its perturbed motion associated with control diminishes rapidly. Such transient processes correspond to a stable ekranoplan, making it easier and more precise to control. Good stability ensures simplified control for the crew of the ekranoplan, allows for full utilization of its maneuvering capabilities, and enhances its safety.

Stability and controllability of the ekranoplan at low altitude can be separately classified as longitudinal and lateral. The latter, in turn, can be divided into course stability and roll stability [13].

Usually, aircraft stability is distinguished regarding load factor (the ability to maintain the load factor of the initial flight regime) and speed stability (the ability of the aircraft to maintain the speed of the initial flight regime without pilot intervention) [14]. Load factor stability of an aircraft depends on the relative position of the center of gravity (CG) and aerodynamic center. With a certain degree of certainty, we can assume that for a load factor stable aircraft, the CG should be located ahead of the center of lift. This can be easily explained with the following example: Let's consider an aircraft with a speed U entering a vertical flow with a speed ω (see Figure 7).

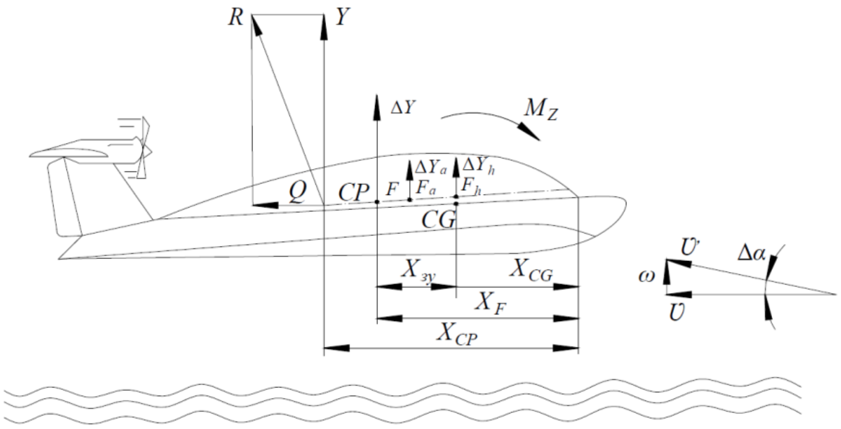

Figure. 7.To determine the aerodynamic focus of the apparatus: -Center of Gravity (CG) - the distance between the aircraft's CG and the leading edge of the wing (aft of the wing's leading edge).

Aerodynamic focus (*F*) - the point at which all aerodynamic forces applied to the aircraft are concentrated. It is typically located slightly behind the CG of the aircraft.

ΔY - increment of lift.

$X_{3y} = X_F - X_{CG}$ - longitudinal static stability margin.

F_h - aerodynamic focus in terms of height.

F_α - aerodynamic focus in terms of angle of attack.

ω - velocity of the vertical airflow.

As a result, the airflow velocity relative to the aircraft becomes U', and the angle of attack increases by $\Delta\alpha$. Consequently, an additional aerodynamic force ΔY is generated at the aircraft's focus. If the center of gravity (CG) is located ahead of the focus, the moment created by ΔY with respect to the CG will pitch the nose down, aiming to decrease the angle of attack, making the aircraft stable under load. If the CG is located behind the focus, the moment created by ΔY will pitch the nose up, further increasing the angle of attack, making the aircraft unstable under load. The stability of aircraft can be studied by conducting wind tunnel tests on models and measuring the corresponding moments. According to convention, the moment that tends to increase the angle of attack (pitch-up moment) is considered positive, while the moment that tends to decrease the angle of attack (pitch-down moment) is considered negative. Usually, when studying longitudinal stability, the focus is not on the moment with respect to the CG (or the leading edge of the wing), but on the dimensionless coefficient of longitudinal moment.

$$m_z = \frac{Mz}{qSb} \tag{2}$$

Furthermore, there is a moment coefficient taken with respect to the leading edge of the wing. In this case, it is denoted as *Cm*. The approximate relationship between the moment coefficient m_z and the angle of attack or the lift coefficient of the aircraft wing is shown in Figure 8.

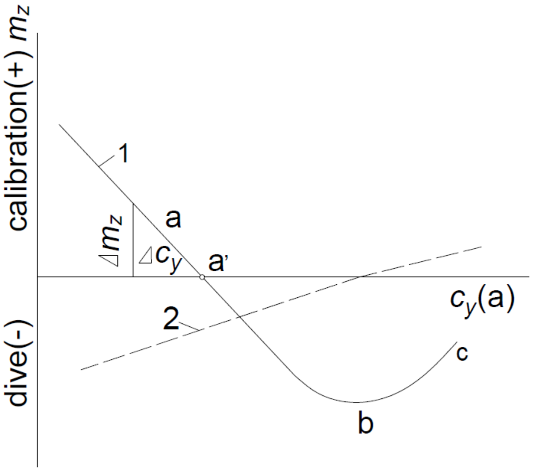

Figure. 8. Dependence of the longitudinal moment coefficient of the aircraft on the angle of attack or lift coefficient:

1 - stable aircraft; 2 - unstable aircraft; a- region of static stability; b - "spoon" - moment of instability onset; c - region of static instability; a' - value of the balancing angle α or lift coefficient Cy ($m_z = 0$).

When the angle of attack increases (for example, due to the aircraft entering an updraft), in the range where the values of m_z decrease with increasing α or Cy, a diving moment arises, which seeks to return the aircraft to its initial flight condition. In this case, the aircraft exhibits longitudinal static stability. Increasing the angle of attack in the region of curve b leads to a decrease in the diving moment, which further increases the angle of attack [15]. The moment of instability onset of the aircraft corresponds to the shallow part of the curve (section b - the so-called "spoon").

Therefore, the condition for longitudinal static stability of the aircraft is a negative value of the ratio of the change in the longitudinal moment coefficient to the corresponding change in the Cy coefficient (or angle α), that is:

$$\frac{\Delta m_z}{\Delta Cy} < 0 \left(\frac{\partial m_z}{\partial Cy}\right) \tag{3}$$

For an unstable aircraft, this ratio has a positive value, that is, $\frac{\partial m_z}{\partial C_y} > 0$. The ratio $\frac{\partial m_z}{\partial C_y}$ (or more accurately, the derivative ∂m_z) is referred to as the coefficient of longitudinal static stability of the aircraft. The absolute value of this ratio characterizes the degree of static stability with respect to load factor.

A negative value of the ratio $\frac{\partial m_z}{\partial C_y}$, and therefore the longitudinal stability of the aircraft, can be achieved by positioning the center of gravity (CG) ahead of the focus. Therefore, the CG position of the aircraft along its length, or what is sometimes referred to as the "balance point," is an important factor affecting the stability of the aircraft.

An equivalent concept of the degree of longitudinal static stability is the so-called margin of stability, which is the distance along the wing chord from the focus to the CG of the aircraft, usually measured in percentage of the mean aerodynamic chord (MAC). MAC represents the chord of a rectangular wing with the same area, equal aerodynamic forces Y and Q, and identical pitching moments with respect to the leading edge of the chord.

It is evident that, to increase the margin of longitudinal static stability, it is necessary to increase the margin of stability, that is, the distance between the CG and the focus of the aircraft (X_F - X_{CG}). One of the most effective means of ensuring longitudinal stability of an aircraft is equipping it with a sufficiently powerful tail assembly, which noticeably shifts the focus of the aircraft towards the tail, thereby increasing the margin of stability.

Ensuring stability for ekranoplans is more complex than for airplanes. The main reason for this is, firstly, the close proximity to the ground or water surface; and secondly, the significant dependence of the wing's center of lift, which moves close to the screen, on the angle of attack and its relative height above the screen.

6. Buoyancy reserve and compartmentalization

6.1 Buoyancy reserve in undamaged condition

The ekranoplan must have a calculated buoyancy reserve of at least 100% at maximum displacement.

The buoyancy reserve should be calculated taking into account the compartments that:

1. Watertight.
2. Have connection dimensions and devices for closing openings recognized by the Registry as sufficient to ensure their watertightness.
3. Below the level of a watertight deck or an equivalent structure that ensures watertightness in the longitudinal and transverse directions [16].

Means of monitoring the watertightness of buoyancy compartments must be provided.

6.2 Freeboard height

The freeboard height of the ekranoplan in displacement mode must be determined in such a way that it meets the requirements of these Regulations regarding buoyancy reserve, intact stability of the vessel, and for passenger ekranoplans, also the requirements for emergency landing and stability [17].

The requirements of the Regulations concerning the cargo mark apply to the ekranoplan to the extent that is reasonable and practicable.

The freeboard height is determined by the difference between the cargo waterline and the top of the watertight deck or equivalent structure that limits the volumes included in the buoyancy reserve [18].

If practicable, the cargo waterline should be marked on the sides or elements of the ekranoplan's structure. The upper edge of this line should correspond to the maximum draft.

7. Mechanical Installations

7.1 General Requirements:

Engines are recommended to be equipped with means for heating or facilitating cold weather starts.

The engine compartment must have forced or natural ventilation, providing the necessary air supply for engine operation and ventilation of the engine compartment. The temperature in the engine compartment should not exceed 70°C [19].

Discharge of bilge water from the engine compartment may only be carried out into designated facilities, for which drainage openings must have a plug or shut-off valve.

Engine controls should be conveniently located at the control station.

On amphibious ekranoplans, the positioning of the engine, transmission and shafts, systems, and propellers should be accessible for inspection and maintenance on the shore platform [20].

Barriers must be provided to prevent accidental entry of people into the danger zone during propeller operation.

7.2 Main Engine Power for the ekranoplans:

The power of the main engines should be such that in the worst allowable conditions when switching the ekranoplan to the screen mode, there is no overload exceeding the limits specified in the engine documentation [21].

7.3 Control Stations:

All actions related to engine and mechanism control must be performed from a single control station of the ekranoplan.

Devices, independent of the remote control system, must be provided for the safe transition of the ekranoplan to the displacement mode [22].

If control of mechanisms, apart from the ekranoplan control station, is also provided from a special station, the transfer of control from one station to another should only be carried out from the control station.

The number of instruments should be kept to a minimum necessary to ensure safe operation [23].

8. Conclusions

By now, many complex problems in ekranoplan construction have been successfully solved through the efforts of scientists and designers from various countries. Experimental vehicles have been created that possess sufficient stability and the ability to fly both close to the supporting surface and beyond the influence of the Earth. Leading foreign specialists, based on accumulated experience, are developing projects for transport ekranoplans weighing up to 300 tons.

Simultaneously with the design work in the field of the ekranoplan construction and the selection of optimal technical solutions, significant attention is paid to assessing the transport efficiency of this new means of transportation, comparing it with the technical, economic, and operational characteristics of ships, surface-effect vehicles, and airplanes.

Despite some achievements by ekranoplan builders and the positive evaluation of the transport efficiency of these vehicles, their development pace is surprisingly low and significantly lags behind the well-known forecasts of leading specialists.

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