To the question of calculating the run distance of the lightweight WIG plan at the stage of preliminary design

A N Luchkov
Moscow Aviation Institute (National Research University), 4 Volokolamskoe shosse, Moscow 125993, Russia
a.luchok.n@gmail.com

Abstract. The work is devoted to the study of the take-off characteristics of high-speed vessels of the WIG type. On the basis of the conducted research, a method for calculating the range of range was developed, considering different types of launch devices during take-off from the water surface. The development of such a method is conditioned by the presence in the design of WIG plans of the problem of determining the most advantageous starting device at takeoff from water under given operating conditions. The proposed method is based on the law of momentum conservation. The method takes into account aerodynamic, hydrodynamic characteristics of WIG plans, characteristics of the power plant from the ship's speed. According to the results of this method it is possible to make a decision on the choice of the most advantageous starting device, providing the performance of the technical task at the stage of preliminary or conceptual design of the ekranoplan. Verification of the technique was carried out using data obtained at the stage of running tests of Orion-10 and Orion-20 WIG plans. The satisfactory coincidence of calculation results and experimental data was obtained.

1. Introduction
Modern equipment is a high-tech product with a life cycle. Cost of life cycle is one of the key characteristics of the product as a whole and includes the cost of development, production, operation and utilization [1]. For passenger ekranoplans the question of reduction of life cycle costs is especial because of high cost uncompetitive in comparison with trains, planes, water transport.

To ensure the specified economic characteristics of the designed lightweight ekranoplan it is necessary, in particular, to determine a sufficient take-off distance taking into account the operating conditions. The take-off characteristics of lightweight WIG plans depend on the aero-hydrodynamic characteristics of the configuration, the ship's power structure and the state of the water area on the approaches to the mooring points (water area of the ekranoplans). Operation of the lightweight WIG plan, which has amphibian quality, implies the possibility of loading and unloading passengers and cargo on the unequipped berths and unloading platforms of the mooring points. Determination of the takeoff characteristics of the lightweight ekranoplans can be carried out in the early stages of design based on the results of testing models, prototypes or numerical simulation.

The analysis [2–10] shows that the established approach to the determination of take-off characteristics of screens is based mainly on the results of experiments with large-scale models in wind tunnels and experimental basins. Calculation of takeoff characteristics of ekranoplans is made mainly by the formulas presented in the sources [4, 5, 8, 11]. Most of the formulas given in the above
sources do not take into account on takeoff the force of hydrodynamic resistance of ekranoplans and are almost complete copies of the formulas used in aircraft equipment for runway running [10]. Book [5] provides a more accurate algorithm for calculating the takeoff characteristics of WIG plans, but its use is difficult in view of the application of these formulas’ characteristics of power plants, which are usually in closed access.

It is important to note that to solve the problems at the early stages of design, including the determination of the required traction values at takeoff modes, the use of experiments with models to determine the takeoff and landing characteristics [9], seems unreasonably long and expensive.

The results of this study show that at the early stages of design it is possible to use characteristics of takeoff and landing devices, mechanization, hydro-aerodynamic characteristics in order to determine the takeoff and landing distance.

2. Output of the ekranoplan to the cruise mode
It is accepted that the start of the ekranoplan from the water surface under the wave conditions can be considered as a sequence of the following stages [5]:

1. — displacement;
2. — planing;
3. — "ricocheting": the interaction of the bottom with the ridges of waves;
4. — transition to screen cruising movement without contact with water surface.

Figure 1 shows a typical dependence of forces acting on the screen at the start on the stroke speed, including the required and available traction.

![Figure 1. Schedule of forces by the speed of the light WIG plan.](image)

The data of figure 1 qualitatively demonstrate possible ratios of traction forces and resistance at the beginning of movement. At the same time, aerodynamic unloading of the hull of the ekranoplans at the beginning of movement, i.e., removal of the vessel from the aquatic environment into the air, is carried out with the use of energy mechanization in the form of a blow system, a static air cushion and other types of starting devices.

3. Main types of starting devices
There are various ways to provide take-off characteristics of light passenger ekranoplans with take-off weight up to 15 tons:

- Increase of the power plant thrust-to-weight ratio to 0.30–0.35 take-off weight units;
- Application of lifting and marshalling engines in the ship arrangement;
  - Propeller;
  - Turbojet;
- Application of flexible fence and blow molding to create a static and dynamic air cushion.

The choice of the method of take-off provision during the preliminary design must take into account the technical and economic requirements to the vessel as a whole. Repeated examples are known in the history of screen engineering, when high energy consumption of the blowing system leveled all positive technical and economic effect expected from high aerodynamic quality of the wing under the effect of screen effect, and the ship could not withstand the competition in commercial operation. For future projects of ekranoplans, which in many respects will decide the fate of this mode of transport, the development of the layout, which allows to ensure high technical and economic performance, seems fundamental.
Figure 2. Scheme of the ekranoplan "composite wing" with gas blowing from turbojet engine (view in the plan).

Figure 3. Scheme of gas blowing under the load-bearing wing.

4. Derivation of the formula for calculating the range of the run of the WIG plan

The method for calculating the range of the ekranoplan can be presented in the following stages:

1. Determination of the ekranoplan tear-off speed according to the normative documentation of the project or prototype;
2. Determining the dependencies of the thrust and resistance forces on the speed acting on the device during takeoff, determination of acceleration;
3. Application of kinematic formulas for calculation of range of run.

To begin with, let us derive the formula for calculating the range using Newton's laws and the formula for calculating the range of run through acceleration (1):

\[ L = \frac{V_{ga}^2}{2a_a}, \]

\( L \) — running distance; \( V_{ga} \) — get away speed; \( a_a \) — average acceleration, where the average acceleration can be calculated based on Newton's second law and obtain the average:

\[ a_a = \frac{P_0(V) - X_{hyd}(V) - X_{aer}(V)}{m_0}, \]

\( P_0(V) \) — speed traction control function; \( X_{hyd}(V) \) — function of change in hydrodynamic resistance from speed; \( X_{aer}(V) \) — function of aerodynamic resistance changes from speed; \( m_0 \) — take-off weight.

Expand the subclauses \( P_0(V), X_{aer}(V) \):

\[ a_a = \frac{P_0\phi(V)\phi_a - X_{hyd}(V) - (C_{x_0}\frac{\rho V^2S_c}{2} + \frac{C_{loc}(1-\sigma)\rho V^2S_c}{2})}{m_0}, \]

\( P_0 \) — total engine thrust; \( \phi(V) \) — speed related thrust function; \( \phi_a(V) \) — function that considers the change in propeller traction by speed; \( C_{x_0} \) — drag coefficient; \( \rho \) — air density; \( S_c \) — total wing area; \( C_{loc} \) — lifting factor of the console; \( 1-\sigma \) — Wieselsberger correction factor; \( \lambda_c \) — console extension; \( S_c \) — console space.

Let's multiply the numerator and denominator for free-fall acceleration \( g \) and express equation (4) through design parameters of wing load \( P_s \) and traction \( \overline{P} \):

\[ a_a = g \left( \frac{P_0\phi(v)\phi_a - X_{hyd}(V) - C_{x_0}\frac{q}{P_s} + C_{loc}(1-\sigma)\frac{q}{P_{sc}}}{m_0} \right), \]

\( g \) — free fall acceleration; \( P_0 \) — bench-top traction; \( X_{hyd}(V) \) — relative hydrodynamic resistance; \( q \) — high speed pressure; \( P_s \) — wing load; \( P_{sc} \) — cantilever load.
One can see that the value of acceleration at any given time depends, among other things, on the speed achieved \( V \). In preliminary calculations, the run length formula can be substituted with an acceleration average value corresponding to the velocity value \( V \approx kV_{go} \). Also, through the average relative value we will express hydrodynamic resistance. With this in mind, we can write the following expressions for calculation of the mean acceleration value at run-up:

\[
a_{\text{up}} = g(\bar{P}_{go}(v)\phi_a - \bar{K}_{\text{aer}} - k^2q) \left( C_{wib} \frac{1}{P_s} - \frac{C_{\text{st}}}{\pi \lambda_s} \right)
\]

\( k_{\text{hydr}} \) — average hydrodynamic quality.

To determine the coefficient of \( k \) and the average relative value of hydrodynamic resistance it is necessary to analyze examples of resistance force dependencies for different systems of unloading the ekranoiplan on takeoff. On figures 4, 5 and 6 there are examples of diagrams of change of hydrodynamic resistance on relative speed.

\[\text{Figure 4. Dependence of the relative resistance force acting on a blowing screen [12].}\]

\[\text{Figure 5. Dependence of the relative resistance force, acting on the screen without starting devices [12].}\]

\[\text{Figure 6. Dependence of the relative resistance force, acting on the screen with the starting device in the form of an airbag [11].}\]

The analysis of the dependencies presented in Figures 4, 5 and 6 shows that the value of average acceleration after overcoming a hump of resistance is reached by a ship at the value of the coefficient of relative speed \( k \approx 0.74 \) units.

Average relative hydrodynamic resistance can be expressed through average hydrodynamic quality \( K_{\text{hydr}} \):

\[\text{Average relative hydrodynamic resistance can be expressed through average hydrodynamic quality}\]
Values of average hydrodynamic quality for ekranoplans with different discharge systems at run-up are given in Table 1.

Table 1. Average hydrodynamic quality. The results of determination of the relative resistance WIG integration function.

| Starting device type | No blowing | With blowing | With the starting device in the form of an airbag |
|----------------------|------------|--------------|-----------------------------------------------|
| \( K_{\text{hyd}} \)  | 10.9       | 8.7          | 13.5                                          |

Average hydrodynamic quality \( K_{\text{hyd}} \) is accepted as corresponding to the hydrodynamic quality at the moment of detachment from the aquatic environment, with the released mechanization of the central plane and deflected hovering ailerons of hypothetical arrangement.

In this regard, let's write down the final equation for calculating the range of WIG plans:

\[
L = \frac{V_{x0}^2}{2 \cdot g (P_0 \rho(v) \varphi_s) - \frac{1}{K_{\text{hyd}}} - 0.55q \left( C_{x0} \frac{1}{P_s} - C_{x0}^2 \frac{1 - \sigma}{\pi \lambda_p} \frac{1}{P_w} \right)}.
\]

5. Checking the output formulas
As a test of the formulas will calculate the take-off range for the WIG plan project Orion-10 with a take-off weight of 4500 kg, equipped with a system of blowing, and WIG plan project Orion-20 with a take-off weight of 14500 kg with the propellers of engines installed on the turntable beam (pylon). The results of testing the head samples of ekranoplans of these projects are presented in Tables 2 and 3.

Table 2. Summary table of Orion-20 ekranoplan characteristics.

| Maximum takeoff weight, kg | 14500 |
|-----------------------------|-------|
| Power plant type 1          | 1x turbojet-10B |
| Power plant type 2          | 2x M601 |
| Power plant capacity 1, HP  | 1040  |
| Power pack capacity 2, HP   | 750   |
| \( C_{x0} \)                | 0.095 |
| Breaking speed, m/s         | 47    |
| Range of run, m             | 3155  |

Table 3. Summary table of Orion-10 ekranoplan project characteristics.

| Maximum takeoff weight, kg | 4500  |
|----------------------------|-------|
| Power plant type           | 2x combustion engine |
| Total thrust of the power plant, kgf | 1300  |
| \( C_{x0} \)               | 0.12  |
| Breaking speed, m/s        | 42    |
| Range of run, m            | 1800  |

As a result of the application of the calculation formula (7), the following characteristics of the range of run are obtained:
Table 4. Calculated ranges of the ekranoplan.

|                                | Difference compared to test results, % |
|--------------------------------|----------------------------------------|
| Range of run with blowing Orion-10, m | 644                                   |
| Range of run without blowing Orion-20, m | 3024                                  |

6. Conclusion

The technique of estimation of takeoff range of lightweight ekranoplans at early stages of designing is offered. Verification of the method is carried out using the results of Orion-20 and Orion-10 tests. Comparison of the results of distance calculation according to the proposed method with the results of tests shows a good agreement, which confirms the possibility of using the method at the early stages of design of lightweight ekranoplans with take-off weight up to 15 tons.

References

[1] Strelets D Y, Serebryansky S A and Shkurin M V 2019 A digital approach to aircraft product lifecycle management 12-th Int. Conf. Management of large-scale system development (MLSD)
[2] Belavin N I 1977 Ekranoplans (Leningrad: Shipbuilding Publishing House) p 227
[3] Jia Q, Yang W and Yang Z 2016 Numerical study on aerodynamics of banked wing in ground effect (Shanghai: Tongji University)
[4] Yun L, Bliault A and Doo J 2010 WIG Craft and Ekranoplan (New York: Springer)
[5] Maskalik A I, Kolyzaev B A, Zhukov V I, Radovitsky G L, Sinitsyn D N and Zagorulko L K 2000 Ekranoplans. Features of Theory and Design (St. Petersburg: Shipbuilding Publishing House)
[6] Maskalik AI, Nagapetyan R A, Lukyanov A I and others 2005 Ekranoplans — transport vessels of the XXI century (St. Petersburg: Shipbuilding Publishing House)
[7] Panchenkov A N, Drachev P T and Lyubimov V I 2006 Expertise of ekranoplans (N. Novgorod: VGAVT) p 520
[8] Khimich V L and Chernigin Y P 2011 Design of Power Plants of WIG-Planes. (St. Petersburg: Shipbuilding Publishing House) p 496
[9] Sergeyev V G 2018 Conditions of safety and performance of the target task at formation of the ekranoplan appearance at the preliminary design stage Proc. of the XII Int. Sci. Conf. on Amphibious and Non-aerodrome Av. and Hydroaviation “Hydroaviation Salon-2018” (Moscow: TsAGI )
[10] Arepiev A N 2006 Designing of Light Passenger Planes (Moscow: MAI Publishing House) p 637
[11] Kaljason P S, Fevralskikh A V and Shabarov V V 2014 Mathematical Modeling of Amphibious Aircraft Aerodynamics on an Air Cushion with Aerodynamic Unloading in the Run Mode on an Air Cushion Problems of Strength and Plasticity 76
[12] http://ekranoplan.ru.narod.ru/C_ANOT.htm