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WING-IN-GROUND-EFFECT CRAFT, THE FLYING BOATS (LETAYUSHCHIYE SU--ETC(U)
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WING-IN-GROUND-EFFECT CRAFT, THE FLYING BOATS

[Belavin, N. I.; Letayushchiye suda - ekranoplany; Kater i Yakhty, No. 15, 1968, pp. 12-20; Russian]

[Editor's Introduction]

It is not a coincidence that the development of fundamentally new types of ships has almost always been connected with the construction of small boats. It is precisely on small, comparatively inexpensive ships and boats that one can conveniently conduct experiments and attain high speeds using moderate power from the power plant. Surface skimmers, catamarans, hydrofoils, and air cushion vehicles -- all of them began from small boats.

It is worth noting that the successes achieved were then rapidly used on larger vessels, producing great economy. It is possible that this could happen with WIG hovercraft as well, although at the present time (at the experimental stage) their dimensions and cargo-lifting capacity are not great. It is difficult now to talk about the prospects for putting WIGs into service, but probable areas of use could be associated with the ability of these craft to operate over various surfaces and at high speeds. Fast patrol WIGs will probably be developed for the vast marshy and reed-covered river mouths. It is possible that sportsmen will take up interest in them.

This article by N. I. Belavin, Candidate of Technical Sciences, will acquaint readers with the basic principles of WIG design and propulsion.

[Belavin's Article]

For over a hundred years shipbuilding engineers, in striving to increase speed, have attempted to pull boats out of the water and put them in the air, a medium 840 times less dense than water. Surface skimming, hydrofoils, and air cushions represent stages in the development of this idea, the last of which being wing-in-ground-effect vehicles (WIGs), i.e., craft which utilize the screen, the effect produced by the increased air pressure under the wing near the water surface. It should be mentioned that the screen surface can also be land. Therefore, WIGs, like air cushion vehicles, are amphibious. They can go onto dry land, move over marshy areas, hover over frozen bodies of water, etc.

WIGs (Table I) being built at the present time are far from perfect. Their comparatively low power-to-weight ratio and aerodynamic characteristics ensure a speed from 80 to 150 km/hr. However, specialists have concluded that technically it is quite feasible to increase WIG speed to 350 or more km/hr.

For comparing WIG potential to that of various high speed craft already familiar to us, use is made of such an obvious indicator as the aerohydrodynamic efficiency K which is the ratio of lifting (useful) force of the craft to the magnitude of the medium's drag (water, air). Remember that the value K determines the power needed for the craft to move at a given speed and consequently the size of its power plant, and what is still more important, the fuel consumption.[1]

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1 The reader will find the fundamentals of foil theory in E. A. Aframeyev and V. V. Veynberg's article in issue number 3 of this collection. Here we recall the expression relating power N_p and the basic analytical characteristics of the craft

$$N_p = \frac{G\nu}{75K}$$

where G is its weight and ν is the given velocity.

For surface skimmers with speeds of 60 to 80 km/hr the value of K is 6 to 8. For hydrofoils at similar speeds K is 10 to 12.[2] For air cushion

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2 When speeds are increased to 140-150 km/hr, the K value falls to 5 - (?) because of foil cavitation, while for WIGs it remains constant. This makes the conclusion in favor of WIGs still more obvious.

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vehicles it is 12 to 16 (using a 4-5 air blast), while for planes the lift-drag ratio K is 16 to 17. For present-day WIGs, K values are from 19 to 25. This means, for example, that a WIG requires three times less power than a surface skimmer to move at the same speed.

The problem now is to put this indisputable theoretical advantage into practical form. Most likely, in the not too distant future WIG flying

TABLE I: MAIN TECHNICAL DATA ON WIG VEHICLES

Country	Designation, Designer	Aerodynamic Design, Wing Area in m^2	Yr. of Construction	Crew, No. of Persons	Wt. in Tons: Full	Wt. in Tons: Empty	Wt. in Tons: Payload	Length in Meters	Beam (Span) in m
Finland	T. Kaario's 1st Craft; AEROSLED No. 8, T. Kaario	flying-wing same	1935 1962	1 1	 .4-.5	 .34	~.08 .10-.16	2.44 8.0	1.33 3.0
Sweden	I. Troeng's Craft; AEROBOAT, I. Troeng	same same	1938 1939	4 1	~3 .6	 .5	 .1		
USA	GEM-1 AIRCOPTER, W. Bertelsen	close to that of a flying-wing; 9.6	1960	1	.41	.33	~.08	4.27	2.03
	GEM-2 AIRCOPTER, W. Bertelsen	same	1961	2	.64	.52	.12	5.73	2.33
	GEM-3 AIRCOPTER, W. Bertelsen	same	1962	4	1.14	.82	.32	7.33	2.39
	Lockheed's WIG Vehicle	close to that of an airplane, 18.3	1963	2	.68	.43	~.2	3.95	4.75
	CLIPPER, V.G. Koryagin	same; 11.5	1965	2	.44	~.24	~.2	~5.7	4.9
	N. Dickinson	flying-wing	1963	2	.5	~.3	~.2	7.95	
	SMALL WEILAND-CRAFT Piloted Model, H. Weiland	close to that of an airplane	1964	1	4.3			15.8	9.5
	LARGE WEILAND-CRAFT, H. Weiland	close to that of an airplane (tandem wings)	1964 design	3000 passengers	1000		3000 passengers	213.4	152.4
	X-112, A. Lippisch	airplane; 10.2	1964	1-2	.33	.17	.16	7.7	4.26
	COLUMBIA	flying-wing	under construction since 1965	120-150 passengers	100	60	40 (150 passengers)	55	24.5
	Piloted Model of the COLUMBIA	same	1966	1				7	
USSR	OIIMF-2 (Headed by Yu. A. Budnitskiy)	flying-wing 2.8+8.4=11.2	1965	1	.45	~.32	.1	5	3.2

TABLE I: MAIN TECHNICAL DATA ON WIG VEHICLES (CONTINUED)

Designation, Designer	Ht. in m	K for Design Mode	Design Operating Ht. in m	Speed in km/hr	Engine Power in hp	Type of Propeller	Start-Up System	Stabilization System
T. Kaario's 1st Craft; AEROSLED No. 8, T. Kaario	1.7		.15	22.4 80	1x16 1x50	air propeller same	tiltable wings	stabilizing surfaces
I. Troeng's Craft; AEROBOAT, I. Troeng				111	2x100 1x60	same screw propeller	hydrofoil	hydrofoil
GEM-1 AIRCOPTER, W. Bertelsen		11.4	.05	60-85	1x65	air propeller	telescopic flaps and flaps	air stabilizer
GEM-2 AIRCOPTER, W. Bertelsen			.3	139	1x115	same	same	same
GEM-3 AIRCOPTER, W. Bertelsen	1.68		.46	130	1x150	same	same	same
Lockheed's WIG Vehicle		~14		83	1x50	screw propeller	flaps	water skis
CLIPPER V.G. Koryagin	1.5	~19		110	1x75	same	flaps and nose plates	flaps
N. Dickinson			.13	139	1x190	air propeller	none	same
SMALL WEILAND-CRAFT Piloted Model, H. Weiland			~1.5	148	2x260	same	water skis	air stabilizer
LARGE WEILAND-CRAFT, H. Weiland	7.6			185 (design)	10x20000	air propeller		
X-112, A. Lippisch	1.93	25-30		143	1x25	same	air propeller stream, flaps	same
COLUMBIA		24	2.7	185	5x2270	same	nozzle blower	flaps
Piloted Model of the COLUMBIA						2 air propellers, blower system	blower	
OIIMF-2 (Headed by Yu. A. Budnitskiy)				100-110 (design)	2x18	air propeller	air propeller stream, flaps	flaps

boats will appear over our rivers and lakes. We will not be surprised, just as we are not surprised by the sight of hydrofoils.

From the History of WIGs

Apparently, the first WIG was created by the Finnish engineer T. Kaario. In the winter of 1932 he tested a WIG towed by air sleds over a frozen lake. In 1935-36 Kaario built an improved craft equipped with an engine with an air propeller. Thereafter he continually improved the design of his WIGs. He tested the last modification (Aerosled No. 8) in 1960 (Fig. 1).

In 1939 D. Warner, an American, developed a design of a boat equipped with a system of lifting wings (Fig. 2) while engaged in experiments to reduce drag on high-speed boats. To make it easier to attain the design mode of near-screen flight it was proposed that the craft be equipped with a blower system using two powerful fans.

In the 40's, extensive experiments were carried out in Sweden under the guidance of I. Troeng. Two WIGs were built based on a flying wing design (Fig. 3), i.e., a craft with a lifting wing.

In the postwar years work to develop WIGs proceeded in the U. S. Beginning in 1958 three craft were built and tested by the well-known designer W. Bertelsen. These "Aircopters," GEM-1 (Fig. 4), GEM-2, and GEM-3, were built to about the same design, but in different sizes. N. Dickinson built a 2-seater WIG, the "flying wing," with an air thrust propeller (Fig. 5). The American firm Lockheed conducted tests on three craft, the last of which is shown in Fig. 6 ("flying boat").

A self-propelled piloted model of the 1,000 ton transcontinental passenger WIG GREAT WEILANDCRAFT (Fig. 7) was built according to H. Weiland's design. This is a 4-ton catamaran with 2 lifting wings placed one behind the other (tandem type). During the first flight test the model broke apart.

The "Aerofoilboat X-112" designed by A. Lippisch was built according to a purely aircraft design and reminds one of a hydroplane (Fig. 8).

In Japan, Kawasaki is successfully engaged in WIG development. Its KAG-3 craft (Fig. 9) is a catamaran with a lifting wing and powerful outboard engine. A more detailed description of it is given in the next article.

A very interesting design for a 2-motor WIG transport was developed by the aviation designer P. I. Grokhovskiy in our [USSR] country as early as the 1930s.[3] A single seater WIG with 2 motorcycle engines, built with

3 See N. N. Bobrov's book The Earth Below, 1935.

a "flying wing" configuration, was built by students at the Odessa Institute of Merchant Marine Engineers under Yu. A. Budnitskiy (Fig. 10).

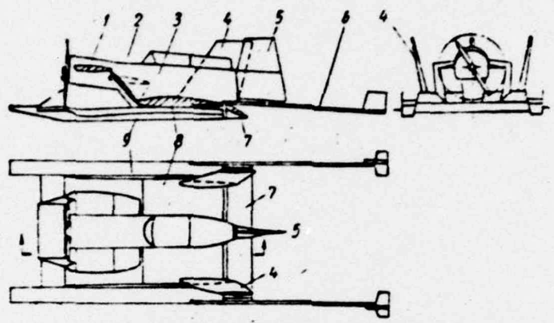


Fig. 1. Diagram of T. Kaario's AEROSLED No. 8.
1 - nose wing; 2 - tiltable directional wing; 3 - hull with cockpit; 4 - lateral stabilizers; 5 - rudder; 6 - tail stabilizing beams with planes.

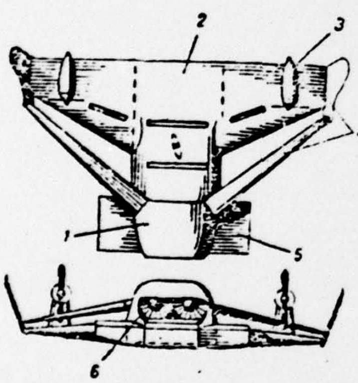


Fig. 2. Diagram of D. Warner's Craft.
1 - hull; 2 - main lifting wing; 3 - engine; 4 - stabilization and control surfaces; 5 - nose wing; 6 - fans for the blower system.

Fig. 3. L Troeng's AEROBOAT WIG. A small stabilizing hydrofoil can be seen in the tail part of the lifting wing.

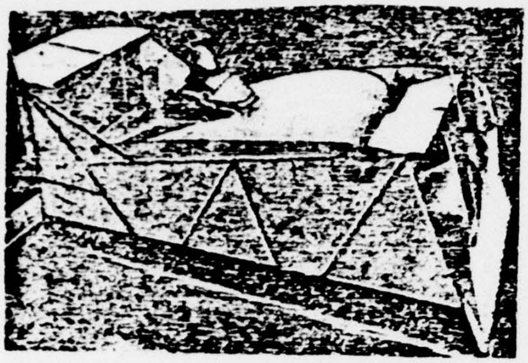


Fig. 4. W. Bertelsen's GEM-1 AIRCOPTER.

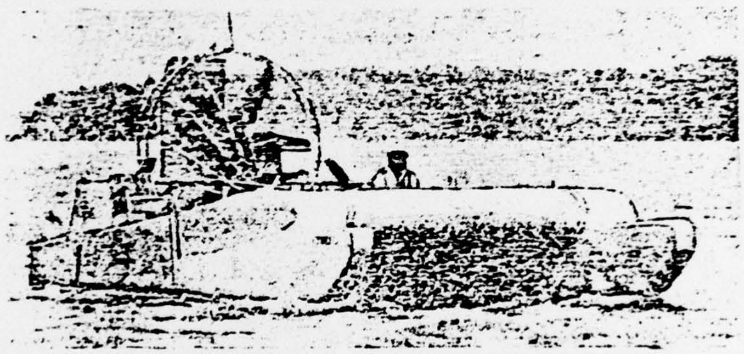


Fig. 5. N. Dickinson's WIG.

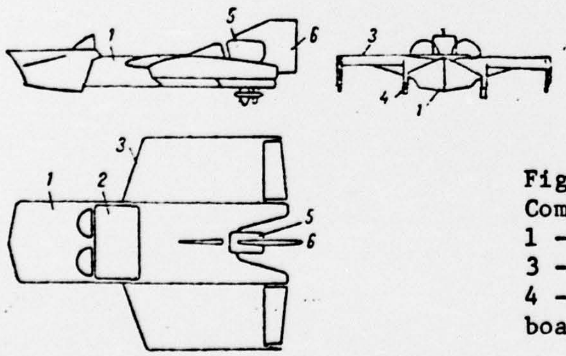


Fig. 6. Diagram of the Lockheed Company's CLIPPER.
1 - hull; 2 - open 2-man cabin; 3 - lifting wing with end plates; 4 - hull nose plates; 5 - outboard engine; 6 - air rudder.

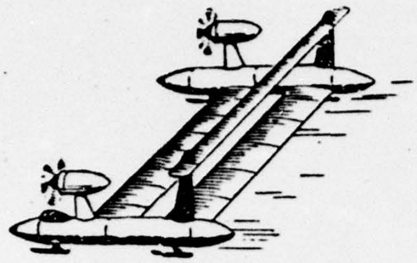


Fig. 7. General view diagram of H. Weiland's self-propelled model (SMALL WEILANDCRAFT)

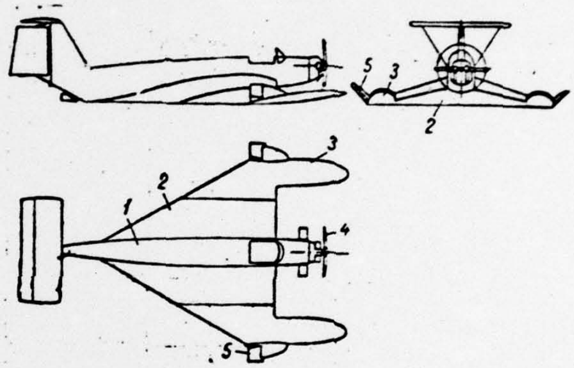


Fig. 8. Diagram of A. Lippisch's X-112 WIG.
1 - hull; 2 - lifting wing;
3 - float plates; 4 - engine;
5 - ailerons.

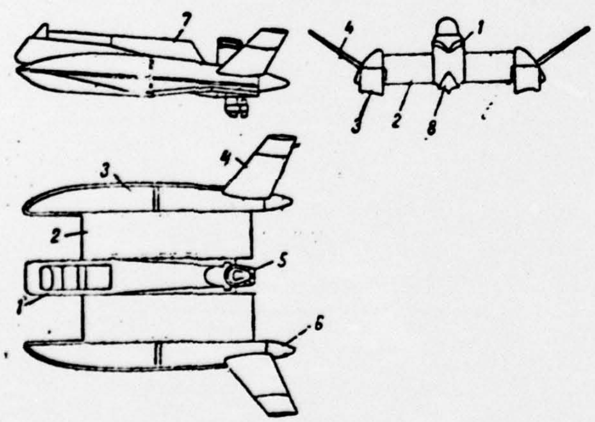


Fig. 9. Diagram of the KAG-3 WIG.
1 - hull with pilot's cabin;
2 - lifting wing; 3 - float plates; 4 - stabilizer with control surface; 5 - outboard motor;
6 - cowling; 7 - cowling;
8 - skimming structure.

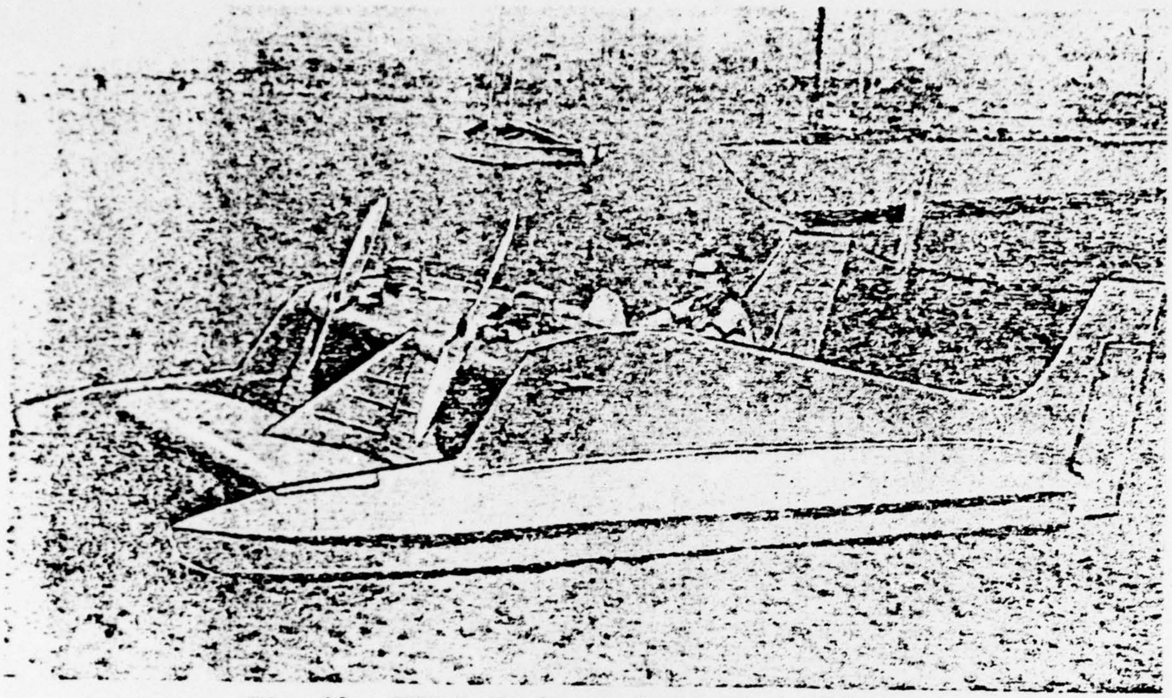


Fig. 10. WIG built by students of the Odessa Institute of Merchant Marine Engineers (OIIMF).

WIG Aerodynamics

The position of the wing above the screen is characterized by the relative height $\bar{h} = \frac{h}{b}$, where h is the height of the trailing edge of the wing over the screen, and b is the wing chord. It has been established that the influence of the screen on operation begins to show at $\bar{h} < 1$, i. e., during the movement at a height which is less than the chord. In this case, while air is being forced between the wing and screen, intense flow braking occurs, and consequently, sharply increased pressure (Fig. 11), i.e., formation of an air cushion, significantly raising the lifting power of the wing. For 2-8° angles of attack this increase in lifting force is 40-45% (Fig. 12).

Due to the proximity of the surface, wing drag is reduced, primarily on account of lowering its induced drag (Fig. 13). Recall that the cause of induced drag is vortices which occur at the ends of the wing as a result of air flow from under the lower surface (increased pressure area) to the upper (rarefaction area). Profile drag caused by friction and pressure forces changes comparatively little as the wing approaches the screen.

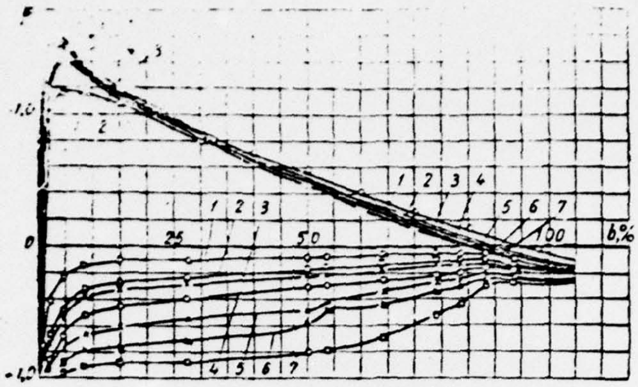


Fig. 11. Pressure change $\overline{p}$ on the wing as a function of $\overline{h}$.
1 - $\overline{h} = \infty$; 2 - $\overline{h} = 0.75$; 3 - $\overline{h} = 0.5$; 4 - $\overline{h} = 0.25$; 5 - $\overline{h} = 0.125$; 6 - $\overline{h} = 0.06$; 7 - $\overline{h} = 0.03$.

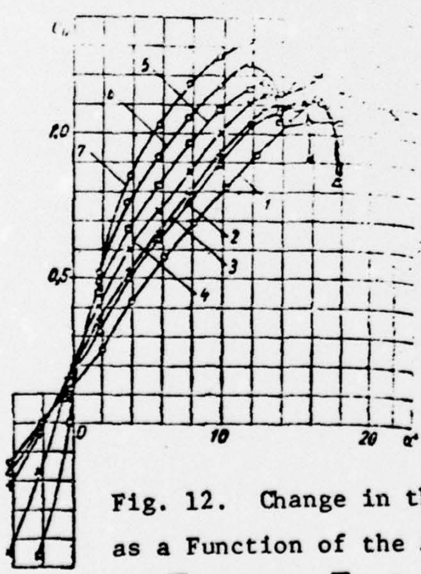


Fig. 12. Change in the Lift Coefficient C_L as a Function of the Angle of Attack α.
1 - $\overline{h} = \infty$; 2 - $\overline{h} = 0.75$; 3 - $\overline{h}$ = (?); 4 - $\overline{h} = 0.25$; 5 - $\overline{h} = 0.125$; 6 - $\overline{h}$ = (?); 7 - $\overline{h} = 0.03$.

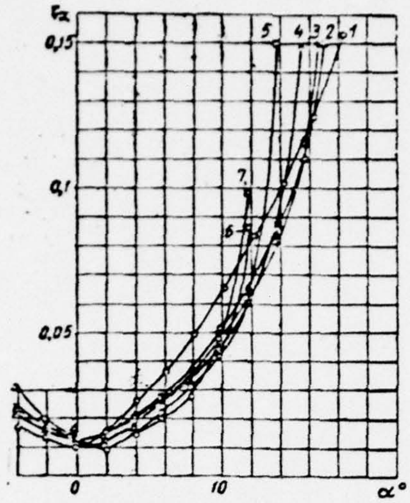


Fig. 13. Change of wing drag coefficient C_D as a function of $\bar{h}$ and the angle of attack α.
1 - $\bar{h} = \infty$; 2 - $\bar{h} = 0.75$; 3 - $\bar{h} = 0.5$; 4 - $\bar{h}$ - 0.25;
5 - $\bar{h} = 0.125$; 6 - $\bar{h} = 0.06$; 7 - $\bar{h} = 0.03$.

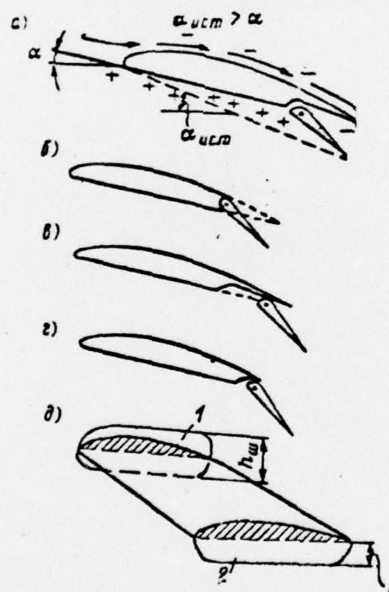


Fig. 14. Systems to increase I of WIG sings.
a - flow pattern of a simple flap covered on top;
b - simple flap; c - simple flap with a sliding rotating axis; d - slotted flap with a shaped slot;
e - end plates: 1 - two-sided; 2 - one-sided.

As the wing approaches the screen, the K value can increase 1.5-2 or more times in comparison with that obtained at greater heights. It can be noted that under these circumstances the maximum values of $\bar{K}$ are achieved at smaller angles of attack. Naturally, near the screen, just as at greater heights, K depends strongly on the characteristics of the wing itself. We note that the wing profiles used on WIGs differ little in their basic characteristics. The OIIMF-2 WIG uses a relative profile thickness of 10-12%.

In analyzing the wing area, the determining value is the specific load per unit area. For existing WIGs this value is comparatively small (35-50 kg/m^2), because of the desire to limit experimental crafts' engine power.

Devices for Improving Wing Quality

For improving flying, and especially take-off and landing characteristics of WIGs, their wings are equipped with flaps and end plates. Rotating wings are used.

We recall that inclining of the flaps increases the lift of a wing by increasing the concavity of its profile. End plates lessen the air flow over wing tips, but near the screen they provide for the formation of a semi-closed zone under the wing with an area of increased pressure. One-sides plates, placed only on the lower side of the wing are usually used on the WIG.

Special Features of Aerohydrodynamic Configuration

There are two basic WIG configurations: the "flying wing" and the aircraft. The first is characterized by a lifting wing whose tips rest on two floats which simultaneously act as end plates. The advantages of this configuration are high aerodynamic efficiency (due to the absence of a fuselage and superstructures) and the possibility of using spaces in this wing for cargo. The basic defect is the difficulty of solving the problem of seagoing properties and stability, especially for small craft.

In the aircraft configuration the fuselage has a great effect, lowering the efficiency, because of the small aspect ratio λ. Nonetheless, low aspect-ratio wings have been used on the majority of modern WIGs (Weiland's Model X is an exception), since with an increased $\lambda = \frac{l}{b}$, the seagoing and operational qualities of the craft deteriorate. For example, there is a danger of a wing tip coming in contact with a wave crest. For a given wing area, the necessary K value can be obtained by decreasing $\bar{h}$, which at a given height requires, as is well known, an increased wing chord, i.e., a corresponding decrease of λ.

Stability

A WIG, like an airplane, must be able to maintain a given flight mode and return to it independently (without pilot intervention) after, for example, a wind gust. When the craft is in motion, the longitudinal stability is due to a considerable degree to the locations of its center of gravity (CG) and aerodynamic center F (Fig. 15), i.e., points relative to which the moment of full aerodynamic force of the wing does not depend on the angle of attack at a constant flight velocity. If the aircraft's center of gravity is in front of the dynamic center, the craft has static longitudinal stability (with respect to loading). For WIGs the problem of stability is considerably more complex since the position of the WIG wing's aerodynamic center does not depend on just the angle of attack, but on $\bar{h}$ as well.

It has been established by wind tunnel model testing that commonly used wings do not have longitudinal stability. Therefore all modern WIGs (like airplanes) have to be equipped with stabilizers or other devices which shift their F to the craft's tail (in so doing, the distance between the center of gravity and F increases). The most successful solution to the problem of longitudinal stability is found on the X-112 where it is achieved mainly with a stabilizer placed high on the vertical tail surfaces beyond the screen effect.

As far as the lateral stability is concerned, WIGs practically always exhibit it. During listing of the craft the lift on the wing which approaches the screen increases and a righting moment is produced.

Directional (course keeping) stability is provided by approximately the same techniques which are used in aviation, i.e., by the appropriate selection of vertical rudder area (air rudder) and its position relative to the WIG's center of gravity. The craft's general configuration, and particularly the position of the point of application of the propeller thrust, plays an essential role in this, of course.

Controllability

One or two air rudders are usually used for heading control. For improving effectiveness they are usually located in the propeller's air stream. When a screw propeller is used, the common water rudder or outboard motor is used.

Drifting while turning, which is peculiar to WIGs, presents a well-known complication becuase these craft have neither submerged hulls nor do they carry foil struts. The possibilities for performing banked turns are limited by the dangerous proximity to the water or land surface.

For steering in a longitudinal plane, practically all WIGs, including propeller craft, are equipped with an elevator or flap. This gear is also used for starting and balancing WIGs in a selected flight mode.

Control of the craft in a lateral plane, i.e., when banking, which is necessary for counteracting turning moments and negotiating sharp turns, is accomplished with the help of ailerons and ailevators (i.e., ailerons which additionally function as elevators), or drooped ailerons (i.e., ailerons which can also operate in a flap mode). The area of these supplementary surfaces is rather large since the speed of the WIG is still considerably less than the speed of an airplane. Thus, the total area of the V-shaped tail assembly on the KAG-3 is 3.2 m^2 or about 35% of the area of the lifting wing.

Engines and Propellers

The power of WIG engines is, as a rule, comparatibely small. In relation to the full weight of a WIG it varies from 80 to 160 hp/t. Most modern WIGs are propelled by an aircraft propeller. Its merits are obvious: the feasibility of attaining high speeds and ensuring amphibious characteristics of the craft.

More rarely, a propeller operating in water is used. Its positive aspects are the comparatively small dimensions, negligible noise, and most important, its higher efficiency at speeds up to 100-120 km/hr. So, the specific thrust developed by air propellers while the craft is moored varies from 2-3 kg/hp, while in screw propellers it reaches 4-5 kg/hp.

Lift-Off Systems

To move into the basic operating mode, the WIG, just as the seaplane and ship, should develop a speed at which the lift of the wings, which raises the craft from the water, becomes equal to the weight of the craft. Model testing has established that the maximum drag (the "hump" on the drag curve) occurs at speeds of 40 to 60% of the lift-off speed.

It can be seen from Fig. 16 that drag hump R is a result of the increase of its hydrodynamic component W at increased speed in waterborne mode. It is precisely to the drag hump (at critical speed v_{cr}) that the minimal value of the lift-drag ratio K of the WIG corresponds. If the maximum propeller thrust is inadequate (curve 1), the WIG cannot overcome the drag hump and will continue to skim with a speed corresponding to point α.

How fast the drag changes during the take-off run can be seen, for example, from the drag curve of the X-112 WIG (Fig. 17). Upon entering the

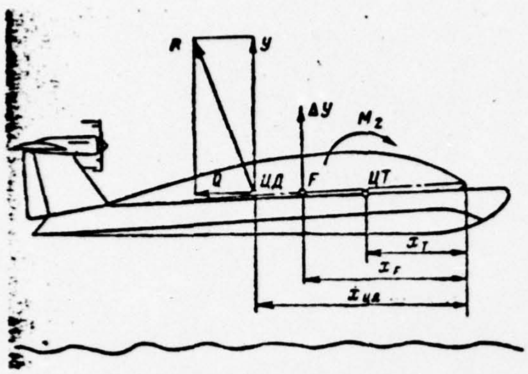
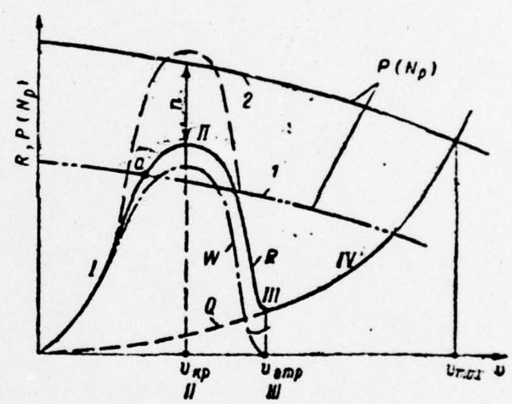


Fig. 15. Diagram for determining the aerodynamic center of a craft. CG = center of gravity; F = aerodynamic center; APC = aerodynamic pressure center; ΔY = lift force increment (wind gust from below); M_z = effective (peak) moment.

Fig. 16. Curves of the WIG engine drag and thrust components. N_p = maximum value of power plant thrust P; R = Q+W -- total drag of the WIG, equal to that which is necessary to be overcome by thrust P; W = hydrodynamic component of drag R; Q = aerodynamic component of drag R; I = waterborne mode; II = skimming mode; III = lift-off from the water at speed $v_{lift\text{-}off}$ and beginning of design mode; IV = near-screen flight mode; n = power plant excess thrust (power) at the hump necessary to overcome the additional increase W in a seaway, etc.; v_{max} = maximum attainable velocity at a given N_p.



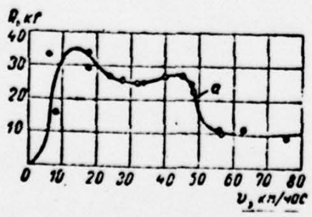


Fig. 17. Tow drag of the X-112 WIG when entering the design mode. α - craft lift-off from the water and beginning of the design mode of near-screen flight.

design mode, R dropped from 25-35 kg to 10 kg and the force-drag ratio K (when weight D = 231 kg) increased from 7.7 to 23.

For overcoming the drag hump during the take-off run and entering the design mode, it would be necessary to briefly increase engine power by 2.5 to 3.5 times in comparison with that which is necessary for flight. In practice, the increase in the lift pushing the hull out of the water at the moment of the take-off is achieved by the use of some type of lift-off systems: flaps, slats, tiltable wings, water skis, and blower systems. On Aerosled No. 8, for example, there are two small tiltable wings placed between the side plates in the air propeller stream. During lift-off the middle wing is positioned using the hand drive in such a way, that the air stream thrown off by the propeller is directed under the main lifting wing. As a result, an air cushion with increased pressure is formed in the half-enclosed space under the lifting wing bounded on the sides by semi-floats and in the tail section by lowered flaps. Thus, even when there is no forward motion, a considerable lifting force develops on the wing, lifting the craft out of the water.

A lift-off system in the form of water skis, i.e., foils of very low aspect ratio (λ = 0.1--0.2 and less) has only been used on the WEILAND X WIG. It is considered that the rather high force-drag ratio (K = 5 to 6), the possibility of lowering the craft's G-force during motion in a seaway, and simplicity are the advantages of the water ski.

A lift-off system in the form of a special blower system consisting of two fans with gas turbine drive is used only on the COLUMBIA WIG.

The lift-off systems can also be used for decreasing the G-force during landings, especially under complex hydrometeorological conditions.

Hull Design

In the design of the hull, flaps, wings, and other components, modern WIGs are much like airplanes. Most craft are made from light alloys, for the most part aluminum alloys, with the thickness of the skin and framing between 0.5 - 2.0 mm (e.g., the OIIMF WIG).

The W. Bertelsen's craft which use a truss structure made of light steel tubes and dural skin differ somewhat from others. N. Dickinson's WIG structure is unique. The lifting wing and floats are made of continuous foam plastic bars tied together by a steel cable.

New structural materials are being used on an ever increasing scale. Part of the KAG-3's skin, for example, is made from glass fiber reinforced plastic.

More about the fundamentals of theory and construction of flying boats can be found in N. I. Belavin's book WIGS, published by Sudostroyeniye Publishing House. (Editor)