Available online at www.sciencedirect.com
ScienceDirect
Progress in Aerospace Sciences 42 (2006) 211–283
PROGRESS IN AEROSPACE SCIENCES
www.elsevier.com/locate/paerosci

Wing-in-ground effect vehicles

Kirill V. Rozhdestvensky*

Saint-Petersburg State Marine Technical University, Lotsmanskaya 3, Saint-Petersburg, 190008, Russia

Available online 28 November 2006

Abstract

This survey has the objective of reviewing research and development of wing-in-ground effect technology. Starting with definitions of the phenomenon and the craft which takes advantage of the ground effect (GE), the history and perspectives of the technology, specific vehicles and projects, and areas of application are covered. Special attention is paid to GE aerodynamics, its mathematical modeling and the stability of longitudinal motion. Also briefly discussed are issues of motion control, structural design, materials and economics. Covered in more detail are matters related to rules of classification, safety and certification. Conclusions are followed by a bibliography, including about 769 entries.

Contents

*Tel./fax: +7 812 714 2923.
E-mail addresses: kvr@smtu.ru, kvrxmas@yahoo.com (K.V. Rozhdestvensky).

doi:10.1016/j.paerosci.2006.10.001

1. Introduction

This survey is dedicated to the memory of a distinguished Russian engineer Rostislav E. Alexeyev who was the first in the world to develop the largest ground-effect (GE) machine—*Ekranoplan*. His first creation, the *top secret* project KM became known to the western world as the *Caspian Sea Monster* because of hovering movements of this mammoth craft over the Caspian Sea. The KM became the prototype for many other advanced marine vehicles utilizing favorable influence of the underlying surface upon aerodynamics and economics, Fig. 1.

The story of the *Caspian Sea Monster* has acquired a publicity, which far surpassed that of the *Loch Ness Monster*. These two tales may appear similar to an uninformed reader. In fact, loch means a lake in Gaelic, and the Caspian Sea is often viewed as an enormous lake. Both monsters were huge and tended to avoid the human eye. Actually, only a *few lucky ones* saw them "in flesh", and both had to be identified from photos.

With the end of the Cold War, the mystery of the Caspian Sea Monster exists no more. But the breathtaking technology behind the development of large flying ships taking advantage of the surface effect at aviation speeds may revolutionize the future fast sea transportation.

1.1. Definitions of the ground effect and wing-in-ground effect vehicles

In what follows "the ground effect (GE)" is understood as an increase of the lift-to-drag ratio of a lifting system at small relative distances from an underlying surface [1]. More general definitions may be introduced, e.g. Reeves defines the GE *as a phenomenon of aerodynamic, aeroelastic and aeroacoustic impacts on platforms flying in close proximity to an underlying surface* [2]. The term "extreme ground effect (EGE)" implies a range of relative ground clearances of 10% of the chord of the main wing or less [3].

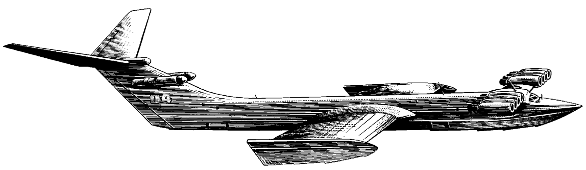

Fig. 1. The KM dubbed "The Caspian Sea Monster".

A wing-in-ground (WIG) effect vehicle can be defined as a heavier than air vehicle with an engine, which is designed to operate in proximity to an underlying surface for efficient utilization of the GE.

1.2. Different names of WIG effect craft

At present many terms exist to designate such a craft. The names *ekranoplan* (from the French word ékran = screen), *nizkolet* (low flying vehicle), *ekranolet* (vehicle able to fly in and out of GE) originated from Russia (R. Alexeev) [4]. *WIG* is a popular abbreviation of WIG effect vehicle. *WISES* (introduced by S. Kubo, Japan) spells as Wing-In-Surface Effect Ship. *GEM* (Bertelson, USA) stands for *GE Machine*. The terms *Flaircraft*, *Tandem-Aerofoil Boat* were introduced by Günther Jörg (Germany). The Lippisch craft derivatives developed by Hanno Fischer (Germany) are called *Airfish*. The technology of air-cushion-assisted takeoff, applied by Fischer, got an imprint in the term *Hoverwing*. The vehicles of Techno Trans (Germany) are known as *Hydrowing*(s). S. Hooker (Aerocon, USA) coined the term *Wingship* designating WIG vehicles of mammoth size [5] As per Hooker, this term "designates very specifically a ship-sized winged craft that ordinarily takes off from and lands in water and which flies at high speed". The term *RAM Wing* applies to the WIG vehicles for which the main contribution to the lift is due to stagnated flow under the main wing. A WIG vehicle permanently using *power augmentation* to enhance the dynamic lift is sometimes called *PARWIG*.

1.3. Distinctions from existing airborne and waterborne vehicles

The WIG effect vehicle *differs from a conventional airplane* by the relatively small aspect ratio of the

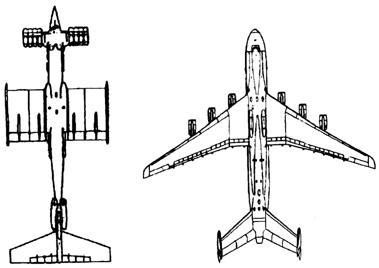

Fig. 2. WIG versus airplane (KM versus AN-225 "Mria").

main wing, endplates (floats), special takeoff and alighting gear (takeoff or liftoff aids). The distinction from a conventional airplane can be seen from Fig. 2, comparing the KM ekranoplan with the AN-225 ("Mria") aircraft of similar size and weight.

The Soviet Military encyclopedia adds to this list of distinctions of the ekranoplan the "raised location of the horizontal tail unit, beyond the limits of the influence of the ground and the wing wake, to ensure longitudinal stability" [6]. Note that the latter feature may degenerate or completely vanish from some configurations such as "tandem", "flying wing" or "composite wing". Contrary to the aircraft the WIG vehicles do not have to be hermetic. Conventional seaplanes versus WIGs have: much larger aspect ratio and higher positioning of the main wing with respect to the hull, i.e. are less subject to the action of GE. Seaplanes (except Bartini's VVA-14) are of airplane aerodynamic configuration. As compared to the hovercraft which is borne by a static air cushion, the WIG is supported by a dynamic air cushion that forms under the lifting wings at large speeds (RAM or chord-dominated GE) or/and by the wing-generated lift enhanced due to reduction of the down wash near the ground (span-dominated GE). While sharing some features with high-powered planing boats, the WIG is supported by dynamic pressure of the air whereas the planing boat is supported by the dynamic pressure of the water.

2. A brief history of WIG effect vehicles

2.1. First inventions and applications based on the GE technology

The earliest practical albeit unintentional utilization of GE belongs to the Wright brothers. The aviators encountered GE phenomena under the disguise of what was called a "cushioning effect" or a "pancake" landing. The transatlantic service of the seaplane Dornier DO-X demonstrated augmentation of the payload and range (1930–1931). Improved ride and handling qualities of conventional military aircraft (F105D, B-58, Avro Vulkan) even at distances exceeding five span lengths above the ground were regularly experienced, see [5].

The first purposefully designed GE vehicle was due to Kaario (Finland, 1935) [7]. His "Aerosledge No. 8" featured a small-aspect ratio wing, leaning upon the skis (skegs) and a swiveling wing, directing the air propeller jet under the main wing. To provide additional static stability margin Kaario added two longitudinal rear beams with small stabilizing surfaces [4], Fig. 3.

A precursor of the power augmentation system can be found in the Warner "compressor" airplane (USA, 1928) [4], Fig. 4. The design was based on a canard configuration and included two powerful fans forcing the air under a dome-like bottom of the vehicle. The Warner was the first to use separate takeoff and cruise engines.

The ram-wing concept was implemented by Troeng (Sweden, 30s) [4], Fig. 5. Particular features of Troeng's rectangular-wing vehicles were: (1) enhanced static stability during takeoff with the help of special floats, (2) use of a screw propeller, (3) use of a small hydrofoil at the trailing edge of the ram wing to ensure longitudinal stability in the design cruising mode.

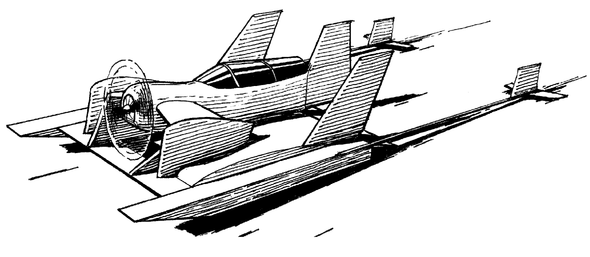

Fig. 3. Kaario's Aerosledge No. 8.

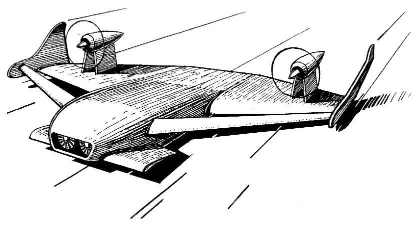

Fig. 4. Warner's "Compressor" airplane.

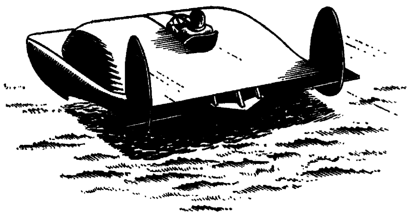

Fig. 5. Troeng's ram wing.

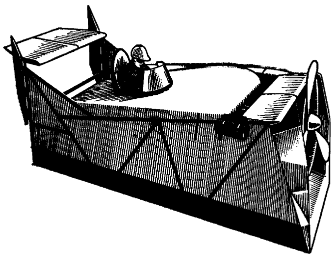

Fig. 6. Ground-effect machine designed by Bertelson.

2.2. Projects and vehicles worldwide

Further extension of Kaario's idea to combine features of WIG effect and air-cushion vehicles was implemented in Bertelson's (USA, late 50s–early 60s) GEMs [4], Fig. 6. Similar to Kaario's design, the GEMs had a single engine for takeoff and cruise. They took off and cruised by means of an air cushion generated by deflecting the propeller air stream under off the main wing. Stabilization of the vehicle was provided by a number of control surfaces: small forward flaps, mounted right after the propeller, and high-mounted albeit small tail plane.

Lockheed had been involved in WIG craft development since 1960. In 1963 a small two-seat boat with a wing fitted with endplates was launched (Koryagin). It had two bow hydroskis for better longitudinal stability [4]. A similar cutter "Clipper" was built in 1965. Beside cutters, Lockheed is known to have studied a large WIG effect flying catamaran. The vehicle was to be stabilized and controlled by flap ailerons and a tail unit, comprising of vertical and horizontal rudders. The cargo was to be transported in the hulls and the wing.

Later, Lockheed-Georgia (see DARPA Report [8]) studied a 1362 million lb (620 tons) wingship, which was designed as a logistics transport capable of transporting about 200 tons over 4000 nautical miles (7410 km) over an open ocean in a sea state 3 environment at a cruise speed of 0.40 Mach. PAR was provided for takeoff and landing with engines cantilevered from the sides of the forward fuselage. The twin vertical and all-movable horizontal empennage is supported from the wing trailing edge by twin tail booms. A single, V-shaped hydrofoil was incorporated into the Lockheed wingship design for landing purposes only. The foil had a span of only 15.2 ft (4.64 m) and a chord of 7.6 ft (2.3 m). The hydrofoil is extended at 150 ft/s (89 knots, i.e. about 165 km/h). Darpa report also describes Northrop Wingship 1.6 M and Douglas Aircraft Wingship-S. The former vehicle has the following main characteristics: TOW = 1.6 mln lb (725 tons), length of 282 ft (86 m), wing span of 141.4 ft (43 m), aspect ratio 2.6, wing loading 206 lb/sq. ft (about 1000 kg/sq m). Structural and empty weight fractions of the vehicle were 32% and 47% correspondingly.

The 2 million lb (910 tons) Douglas Aircraft Wingship-S (1977) was supposed to use the power augmented ram (PAR) wing concept. The underwing cavity pressure was provided from the exhaust of the four canard-mounted engines. In the DAW-S the PAR was used at all speeds and the forward engines were fixed at a certain angle. The underwing pressure is sustained by plain flaps at the rear of the wing and a pressurized inflatable skirt extending vertically along the wing tips. As per the DARPA report, the DAW-S takes off and lands vertically at zero forward speed, thus experiencing no hydrodynamic forces due to forward motion. The wing is mounted flush with the bottom of the fuselage to prevent wave impact. The fuselage, therefore, is similar to the conventional land plane design and has no seaplane keel, chines or deadrise contours and is designed for floating loads only. A substantial ski structure is included under the aft fuselage to assist in the vehicle longitudinal trim during takeoff and landing. A conventional T-tail empennage also maintains trim and stability at forward speeds. Quite a unique craft was developed in the 60s by the Swiss engineer Weiland within his contract with the US company "West Coast" [4]. Weiland vehicles comprise a twin-hull structure with two large wings of aspect ratio 5 configured in a tandem. The "Small Weilandcraft" of 4.3 tons was to be followed by a 1000—ton "Large Weilandcraft" with length in excess of 200 m and width of more than 150 m, Fig. 7. Sufficient attention was attached to providing efficient takeoff.

As an alternative to hydroskis, Weiland proposed power augmentation. He also introduced special

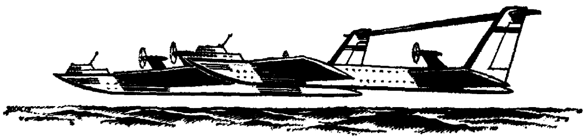

Fig. 7. Weiland's "Large Weilandcraft" Project.

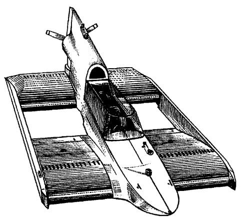

Fig. 8. TAF VIII-1 tandem vehicle (Günther Jörg).

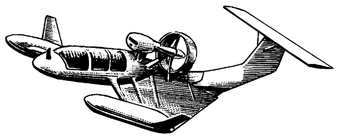

Fig. 9. Lippisch X-114.

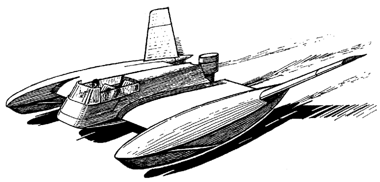

Fig. 10. Kawasaki KAG-3 craft (S. Ando).

inflatable shells on the bottoms of the hulls to reduce the impact of waves during takeoff. The "Small Weilandcraft" crashed during the tests supposedly due to lack of static stability. Beginning from 1963 Günther Jörg in Germany designed and built a series of ground-effect vehicles (TAF = Tandem-Airfoil-Flairboat) based on the idea of arranging two stubby wings in tandem [9], Fig. 8. He was able to ensure static stability and controllability of the vehicle in longitudinal motion by a proper "tuning" of parameters of the forward and rear wings and their design pitch angles. Thereby the longitudinal steering control is reduced to throttle control only.

Lippisch—a German aerodynamicist, who worked for the US company Collins Radio—introduced new WIG effect vehicles based on the reverse delta wing planform. In 1963 he built his first X-112 "Aerofoil Boat". This and the following Lippisch craft had a moderate aspect ratio in excess of 3 and inverse dihedral of the main wing enabling them to elevate the hull with respect to the water surface. The reported lift-to-drag ratios were of the order of 25. Besides, a forward-swept delta wing in combination with a relatively large high-mounted tail plane appear to provide sufficient longitudinal stability in a range of flight heights including cruising close to the ground and dynamic jump modes.

In the 70s the series was extended to the X-114 (takeoff weight of 1.35 tons) which was commissioned by the German Ministry of Defense, Fig. 9. In order to reduce significant loads encountered when landing on the water surface, hydrofoils were mounted on the vehicle, two in the front and one at the stern. Beside these small craft Lippisch also studied the design of much larger machines.

One such design was that of a 300-ton GE machine with a 6-engine power plant of 50,000 hp, able to carry 300 passengers at a cruising speed of 300 km/h [4].

Three types of WIG effect vehicles were developed by the Japanese company Kawasaki (KAG-1, KAG-2 and KAG-3) [4,10]. The vehicles were designed by Ando. The KAG-3 vehicle (takeoff weight of 0.7 ton, length 5.9 m, width with stabilizers about 6.15 m, screw propeller) was built and tested in 1963, Fig. 10.

2.3. Russian ekranoplans

The Russian developments started in the early sixties almost simultaneously in the Taganrog Aviation Construction Complex headed by Beriev and in the Central Hydrofoil Design Bureau (CHDB) in Nizhniy Novgorod [11–13].

The vehicles developed in Taganrog under the guidance of Bartini were seaplanes rather than ekranoplans in the direct sense of the word. The idea behind Bartini's designs was to provide contact-free takeoff and landing of a seaplane using the GE.

Two anti-submarine airplanes named Vertical-takeoff-Amphibia were built possessing improved seaworthiness and being able to takeoff and land at practically any sea state. The development started with the small single-seat seaplane Be-1 built in 1961. It had a low-aspect-ratio main wing between two floats (hulls) and small side wings. The vehicle

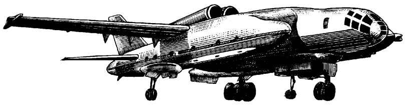

Fig. 11. Vertical-takeoff Amphibia (Bartini, Beriev Bureau).

was propelled by a turbojet engine mounted on the upper side of the main wing. To facilitate liftoff surface-piercing hydrofoils were fitted on the floats. Next was VVA-14 which had a length of 26 m, width of 6 m, takeoff weight of 52 tons and cruising speed of 760 km/h at altitude of 10 km, Fig. 11.

This was essentially a flying catamaran. Its basic part was a small-aspect-ratio center-wing of rectangular planform bounded by two hulls. The fuselage was mounted toward the front part of the wing along its axis and two side wings were fitted behind the center of gravity (CG). The liftoff was to be provided by 12 engines on the center wing. In fact these were power augmentation engines. Two D-30 M turbofan cruise engines were located rearwards above the central wing so that they were protected against water ingestion. Also there were 14-m long inflatable pontoons fitted on the bottom of the side hulls.

However, the main developments of what is now called ekranoplan were made in CHDB by Alexeev's team which viewed the vehicle's flight close to the underlying surface as the main regime of operation. The first piloted ekranoplan SM-1 of 3-ton takeoff weight was based on a tandem scheme (1960). This concept was later discarded because of the high speed of detachment from the water, "stiffness" of flight and narrow range of pitch angles and ground clearance for which this configuration was longitudinally stable.

The 5-ton SM-2 prototype had a new configuration, comprising a low-flying main wing and highmounted tail plane. Another revolutionizing novelty of this vehicle was its capability to pressurize the air under the main wing by the exhaust of the engines located upstream in the front part of the vehicle. Thus emerged a wing-tail configuration with PAR constituting the basis for the following series of ekranoplans of the first generation.

As a result of a huge engineering effort involving development and tests of many self-propelled models there evolved a prototype KM with takeoff weight of 550 tons, length in excess of 90 m, cruise speeds above 500 km/h, main wing of aspect ratio 2, Fig. 1.

The first small-scale KM prototype was the model SM-5 although its tail plane did not feature a dihedral which appeared later on SM-8 and the KM itself. Eight marinized turbofan engines of 10-ton maximum thrust each were mounted on the front pylon forward of the main wing to provide PAR takeoff. Another two identical engines were installed at about mid-height of the vertical stabilizer and were used for cruising. After extensive tests in 1967–69, KM showed: efficient takeoff in waves up to 3 m, smooth flight, amphibious capability (ability of going onto a shallow water area and a beach), and good longitudinal stability in the whole range of design heights.

The next vehicle of the KM family was "Orlyonok" (1973, with 120-ton takeoff weight, length of 60 m, aspect ratio 3 main wing), Fig. 12.

Differently from KM, "Orlyonok" had two PAR engines of 10-ton static thrust "hidden" in the bow part of the fuselage. Cruise propulsion was provided by a 16-ton static thrust turboprop engine, mounted at the intersection of the vertical stabilizer and the tail plane, and two counter-rotating variable pitch propellers with diameter in excess of 6 m. The turboprop engine not only ensured higher efficiency than the jet, but also the variable pitch propellers provided remarkable low-speed maneuverability in the PAR mode.

In 1987, the next representative of the KM family was launched—a missile carrier "Loon" (400-ton takeoff weight, 450 km/h cruising speed, length of 74 m, main wing aspect ratio exceeding 3). Its peculiarity was that (due to the missile launching mission) all eight engines (static thrust of 13 tons each) were mounted on the bow pylon to serve both as PAR and cruise prime movers, Fig. 13.

Another type of Russian WIG effect vehicles is known as Dynamic Air Cushion Ships or DACS [12,14]. The DACS concept was set forth by Alexeev in the late 70 s with designs accommodating from 8 to 250 passengers. The basic element of DACS is a wing of small aspect ratio bounded by skegs (floats) and rear flaps to form a chamber. The dynamic air

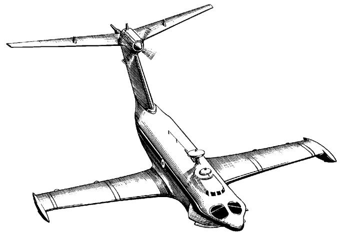

Fig. 12. Ekranoplan "Orlyonok" (Alexeev-Sokolov).

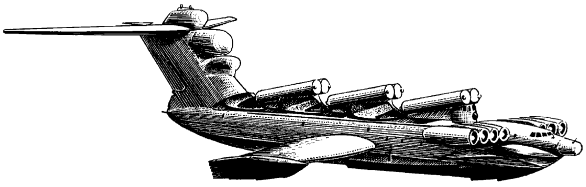

Fig. 13. Ekranoplan "Loon" (Kirillovykh).

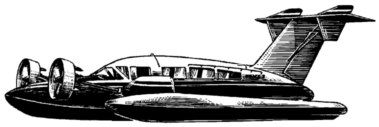

Fig. 14. Dynamic air cushion boat "Volga-2".

cushion in the chamber under the wing is formed by means of blowing of the air with special fans (propellers) mounted in front of the vehicle. The overpressure under the wing equals or exceeds the weight of the vehicle even at zero or small speed. As the speed increases, the augmentation of lift is additionally enhanced due to the dynamic head of the oncoming air. For DACS the blowing (power augmentation) is a permanent feature present both in the cruising and takeoff–touchdown modes. Numerous tests carried out at the CHDB showed that efficiency of DACS is similar to that of hydrofoil ships. At the same time, the speed of DACS far exceeds that of both the hydrofoil ships and the ACVs. The first practical vehicle of DACS type was the Volga-2 cutter, Fig. 14.

This 2.7-ton craft has a length of 11.6 m, width of 7.65 m and height of 3.6 m. The range of cruise speeds of Volga-2 is from 100 to 140 km/h. The vehicle is propelled by the ducted air propellers mounted ahead of the wing. Inclination of their axes and use of special hinged vanes serves to provide both power augmentation and horizontal thrust. The main lifting wing of the craft is almost square and has S-shaped sections to enhance the longitudinal stability. As a result, the latter turns out to be sufficient in spite of the relatively small tail area.

3. Recent projects

3.1. Projects and prototypes produced in China

Development and design of WIG effect craft in China was started in the China Ship Scientific Research Center (CSSRC) in 1967 [15,16]. Since then, during more than 30 years a total of nine small manned test vehicles have been designed and tested on lakes and in coastal waters (see table). The XTW series was based on a wing-tail configuration with the main wing having forward sweep as in Lippisch designs, Fig. 15.

In 1996 the CSSRC reported developing the XTWII, XTW-III and XTW-IV WIG effect craft, Fig. 15. A typical craft of this series is XTW-4 which was slightly modified from XTW-2 to comply with specific requirements from sea trials. This 20-passenger WIG effect ship was first tested on the Changjiang River in the autumn of 1999. The vehicle comprises: a major hull (float), the main wing supported by two minor floats, two vertical stabilizers carrying a high-mounted tail plane. To a certain extent the vehicle can be ascribed to wing-tail configurations. The main wing features the forward sweep, reminiscent of the Lippisch deltawing concept. Two P&WC PT6A-15AG turboprop engines with MT's 5-bladed adjustable pitch propellers are mounted at the leading edge of the main wing. Thus, the slipstream is efficiently used to assist takeoff. Also, the WIG effect sixseat vehicle SDJ 1 using a catamaran configuration was developed [17].

In early eighties another Chinese organization, MARIC, started developing what they called AWIG (Amphibious WIG) [18]. About 80 models were tested to study optimal wing profiles, configuration of the air channel, position of the bow thrusters, arrangement of the tail wing, etc. A self-propelled radio-controlled model of 30 kg was tested on Din-San lake in a suburb of Shanghai. As the model showed acceptable performance, MARIC proceeded to the development of the larger craft AWIG-750 with a maximum TOW of 745 kg, length 8.47 m, span 4.8 m, height 2.43 m, Fig. 16. The power plant included internal combustion engines: two for lift and two for propulsion of the craft. Each engine drove a ducted thruster type DT-30 of 30 hp rated power at 6000 rpm. The vehicle was able to takeoff in waves of 0.5 m and had a

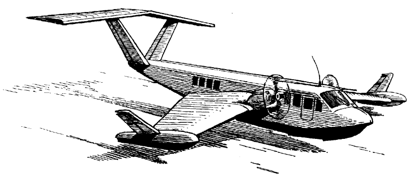

Fig. 15. XTW-1 vehicle (CSSRC, Wuxi, China).

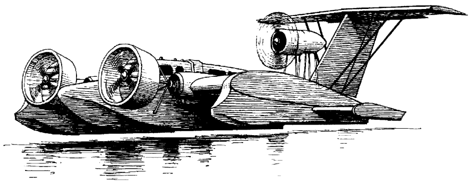

Fig. 16. AWIG-751 (MARIC, China).

maximum speed of 130 km/h. It demonstrated the expected (amphibious) capability of passing from the water to the shore and back.

In 1995, the China State Shipbuilding Corporation commissioned the R&D for a 20-seat AWIG-751 under the name "Swan-I" to MARIC and the Qiu-Sin Shipyard [18], Fig. 16.

The vehicle which was completed by June 1997 had a TOW of 8.1 tons length–width–height dimensions of $19 \times 13.4 \times 5.2\,m^3$ and a maximum cruising speed of 130 km/h in calm water. It had three aviation-type piston engines: two HS6E engines of 257 kW each for PAR lift and one HS6A engine of 210 kW for propulsion. The PAR engines drove two bow ducted 4-bladed air propellers and the cruise engines drove a two-blade variable pitch propeller. As compared to the previous AWIG-750 it had several new features, including: increased span of the main wing, composite wing, combined use of guide vanes and flaps to enhance longitudinal stability, CHIBA composites to reduce structural weight.

The tests confirmed overall compliance with the design requirements, but showed some disadvantages, namely, too long shaft drives of the bow propellers, lower payload and lower ground clearance than expected. The follow-on vehicle AWIG-751G (Swan-II) had increased dimensions, a modified PAR engines layout and an improved composite wing.

3.2. Projects and vehicles developed in Germany

Hanno Fischer, the former technical director of Rein-Flugzeugbau, set up his own company Fischerflugmechanik and extended the Lippisch design concept to develop and build a 2-seat sports vehicle designated as Airfish FF1/FF2 [19], Fig. 17.

Unlike X112 and the following X114, the Airfish was designed to fly only in GE. It was manufactured of GRP and reached a speed of 100 km/h at just half the engine's power during tests in 1988.

In 1990 Fischer Flugmechanik tested a 4-seat vehicle Airfish-3, which was 2.5 times heavier than Airfish FF2, flew at a speed of 120 km/h and was able to cover a range of 370 km [19], Fig. 17. With a length of 9.45 m and a width of 7.93 m, the vehicle had an operational clearance ranging from 0.1 to 1 m. Although the craft was tailored for use in GE, it could perform temporary *dynamic jumps* climbing to a height of 4.5 m.

A design based on the Airfish series formerly developed by Fischer Flugmechanik has re-emerged in Flightship 8 (FS-8 initially designated as Airfish 8) [19], Fig. 18. The FS-8 was developed in Germany by Airfoil Development GmbH and made its maiden flight in the Netherlands in February 2000. With its TOW of 2325 kg, length of 17.22 m, width of 15.50 m and height of 4 m the Flightship-8 carries 8 people, including two crew. The wave height at takeoff is restricted to 0.5 m, but when cruising the vehicle can negotiate 2-m waves. FS-8 is made of FRP. With an installed power of 330 kW it has a cruising speed of about 160 km/h and a range of 365 km. The customer is the Australian Company Flightship Ground Effect Ltd. whose branch Flightship Australia conducted trials of the vehicle in Australia. The R&D and production work is monitored by Germanischer Lloyd with regard to classification of the craft.

A larger Flightship-40 (FS-40) dubbed Dragon-Clipper is being designed for up to 40 passengers in the commuter version for an equivalent payload of 5 tons in alternative configurations. This larger craft has a length of 30 m, and the wingspan of 25 m can be reduced to 20 m for onshore handling by folding winglets. The main construction material is aluminum, and the Pratt and Whitney turboprop-diesel

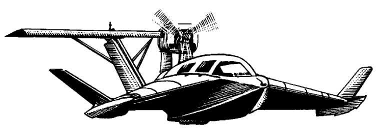

Fig. 17. Airfish 3 (Hanno Fischer).

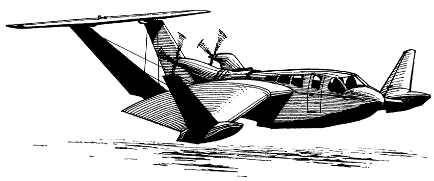

Fig. 18. Airfish 8—Flightship 8 (Hanno Fischer).

engines developing 1000 kW will increase the cruising speed to about 225 km/h. Maximum takeoff wave height is 1.2 m and increased wing span allows over-water operation in 4 m seas. The originators of the FS-8 design Fischer Flugmechanik and AFD Aerofoil Development GmbH have recently announced a proposal to produce a new craft HW20 [20] combining WIG effect and static air-cushion technology (see paragraph 9.2). The design of HW20 (Hoverwing) employs a simple system of retractable flexible skirts to retain an air cushion between the catamaran sponsons of the main hull configuration. This static air cushion is used only during takeoff, thus enabling the vehicle to accelerate with minimal power before making a seamless transition to true GE mode, Fig. 19.

Techno Trans e.V. was established in 1993. The company started its activities by performing quite extensive tests of Joerg tandem craft prior to launching their own WIG effect craft, project Hydrowing [21] with the goal to build an 80-passenger ferry. In the mid-nineties they built a 2-seater prototype (Hydrowing VT 01) propelled by two unducted propellers. The vehicle had a TOW of 812 kg, length of 9.87 m and width of 7.77 m. With installed power of 90 kW it could sustain a cruising speed of 120 0 km/h and could operate in waves of 0.4 m. The main wing of the vehicle had S-shaped cross-sections for better stability, and a high-mounted horizontal stabilizer supported by two vertical fins at the stern [21].

The present project of Techno Trans is designated Hydrowing 06, Fig. 20. It has a TOW of 2.3 tons, installed power of 210 kW, a length of about 14 m, a width of 11 m and a cruising speed of 125 km/h. It also adopts the forward sweep feature of the Lippisch designs, has both air and water rudders, and is equipped with a small hydrofoil for takeoff assistance.

3.3. New vehicles and projects in Russia

3.3.1. Marine Passenger Ekranoplans

A composite wing configuration implies functional subdivision of the craft's lifting area into two

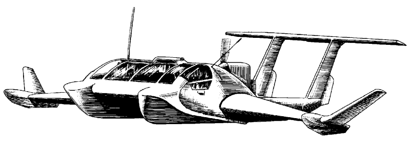

Fig. 19. Hoverwing-20 with a static air-cushion liftoff system.

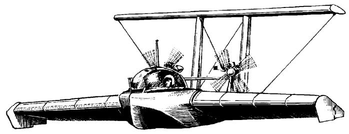

Fig. 20. "Hydrowing" vehicle of Technotrans.

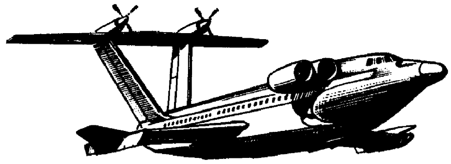

Fig. 21. Marine passenger Ekranoplan MPE-400 (D. Synitsin, T&T—ATT—ATTK).

parts: the one (central) taking advantage of the power augmentation mode, and the one (side wings) adding efficiency and longitudinal stability in cruise. Provision of stability in this case has three major ingredients: special profiling of the central part of the main wing, horizontal tail (albeit relatively small), appropriate geometry and position of the side wings. The designs, exploiting these features, are those of the MPE (Marine Passenger Ekranoplan) series (Designer General D. Synitsin), ranging in TOW from 100 through 400 tons [14], Fig. 21. The MPE-400 project (1993) has a TOW of 400 tons, length of 73 m, width of 53 m and height of 20 m. It is intended to carry 450 passengers. It features an overall aspect ratio of 4.5. For better stability the central wing sections were S-shaped resulting in considerable reduction of the area of the tail plane. The latter constitutes 27% of the area of the main wing. For KM this factor was 50%. Because of the aforementioned specific features the ekranoplans of MPE type can be assigned to the second generation.

3.3.2. Amphistar-Aquaglide series

Ekranoplan Amphistar was developed and built by the company "Technology and Transport" (Director and principal designer D. Synitsin) in 1995 [22]. In 1997 this vehicle was awarded the certificate of the Register of Shipping of the Russian Federation as a *cutter on dynamic air cushion.* The maximum TOW is 2720 kg, its $L \times B \times H$ dimensions are $10.44 \times 5.9 \times 3.35\,\mathrm{m}^3$. At cruising speed of 150 km/h it has a range of up to 450 km. Seaworthiness is about 0.5 m. The turn radius at cruising speed is about 65 hull lengths. In water the turn

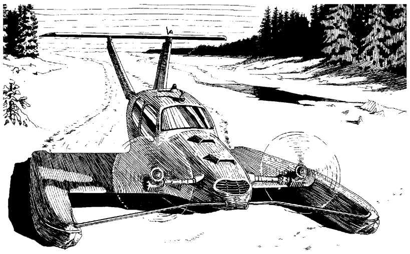

Fig. 22. Aquaglide-5 wing-in-ground effect vehicle (Synitsin, ATT-ATTK).

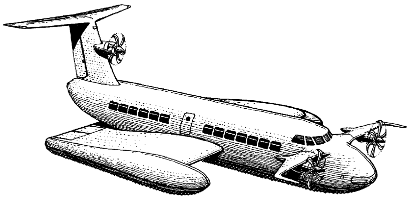

Fig. 23. Aquaglide-50 (project, Synitsin, ATT-ATTK).

radius is about a hull's length. A modified version of the vehicle has recently appeared under the name Aquaglide, Fig. 22. Synitsin developed a scaled up series of Amphistar-Aquaglide-type vehicles, Fig. 23. Another example of larger dynamic air-cushion vehicles scaled up from the Volga-2 cutter is a 90-passenger high-speed river craft Raketa-2 designed to cruise at a speed of 180 km/h for ranges up to 800 km, and powered by a gas turbine. CHDB has also developed a conceptual design of a 250–300 passenger dynamic air-cushion ship Vikhr-2.

3.3.3. Transport Amphibious Platforms (TAP)

This new concept of fast water amphibious transport developed by the CHDB and ATT-ATTK has speeds in the range of those of a hovercraft and WIG effect craft, Figs. 24a and b. Like the Dynamic Air Cushion Craft the TAP are supported both by the dynamic head of the oncoming flow and by that of the jet exhaust of the bow PAR engines. At the same time, the TAP moves in constant contact with the water surface (note that the ATT-ATTK concept of TAPs admits gaps between the vehicle and water surface). High efficiency is achieved through a proper combined use of the aerodynamic GE and high hydrodynamic quality of the elongated planing hulls (floats). The main structural component of the TAP is a cargo platform with longitudinal side skegs, the bow pylon with PAR engines

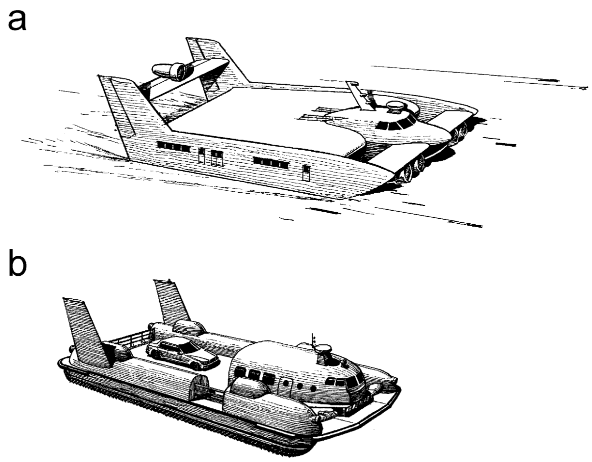

Fig. 24. (a) Transport Amphibious Platform (project, CHDB). (b) Transport Amphibious Platform Aquaglide-60 (project, ATT-ATTK).

and a bow cockpit. The propulsion engines are mounted on the tail plane. The claimed advantages of the TAPs are high-speed (up to 250 km/h), amphibious capacity, ability to carry superheavy and oversized cargoes, high weight efficiency (up to 40–50%) due to a structural scheme simplified versus hovercraft and WIG craft, low specific load on the supporting surface of the skegs (close to that of a skier on a snow surface), making the vehicle ecologically friendly.

The TAPs [23] are claimed to have advantages compared to hovercraft: 2 times larger speed; high seagoing qualities providing stable motion in rough seas without flexible skirts; high cargo-carrying capacity and weight efficiency; relatively simple structure featuring no complicated multi-element power plant with reduction gears, transmissions and hover fans. The TAP aerodynamic efficiency (lift-todrag ratio) is 10–12 at a speed of the order of 135 knots.

3.4. Projects and vehicles in the USA

In the early 90s, a US company named AEROCON developed a project Aerocon Dash 1.6 [8], Fig. 25. This mammoth Wingship had the following physical characteristics: TOW = 5000 tons, payload fraction of 0.3588, wing loading of 258 lb/sq. ft (1260 kg/sq m), cruise speed of 400 knots (740 km/h), cruise altitude of 12 ft (3.66 m). As underlined in the DARPA report, a unique characteristic of the Dash 1.6 is its land overflight capability. A flight altitude of 6000 ft (1830 m) and a speed of 400 knots

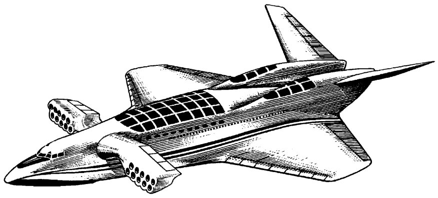

Fig. 25. Aerocon Dash 1.6 "Wingship" (Stephan Hooker).

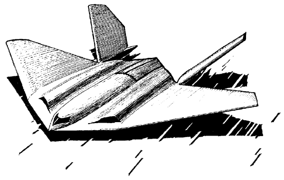

Fig. 26. Lockheed Martin SEA (surface-effect-aircraft) concept.

were assumed for the transit over land barriers. Whereas in free flight lift-to-drag ratio was estimated as 15, in design GE mode the expected value of aerodynamic efficiency was more than 32.

In recent years Lockheed Martin Aeronautical Systems investigated the development of what they call ***Sea-Based Aircraft*** [24]. LMAS calls for a move to hybrid aircraft compliant with a modern doctrine of rapidly moving smaller and lighter forces anywhere in the world, or standoff power projection on demand anywhere in the world. The LMAS search for appropriate hybrid solutions resulted in a family of designs. These include: seaplanes, floatplanes and WIG-like combined surface effects aircraft—SEA, Fig. 26.

LMAS concludes SEA is an emerging more effective alternative to WIG craft.

Whereas the latter

- is a ship that flies (specifically, the Russian Ekranoplans),
- has little altitude or maneuvering capability,
- is sea-restricted,
- has long takeoff roll,
- should be very large for the mission objectives,
- has no signature reduction capacity

the former

- is an aircraft which operates on water,
- has aircraft altitude capability,
- has shorter takeoff roll than pure WIG aircraft,
- may be shaped for signature reduction,
- has reduced risk due to rogue waves and surface obstacles.

SEA combines multiple surface effect technologies in a Sea-Based Mobility Hybrid Aircraft design—WIG, seaplane and hydroplane hull shaping. surface-effect ship hull shaping, ram and power-augmented lift, powered circulation lift and ski ship. According to LMAS, such a concept is viable with the current aircraft technology, and would provide speeds up to 400 knots and a global range with 400 tons of payload.

As reported by Boeing Frontiers (online, September 2002, vol. 01, issue 05), a high-capacity cargo plane concept dubbed Pelican is being developed currently by **Boeing Phantom Works** [25], Fig. 27.

It has a large-aspect-ratio main wing, a wingspan of 500 ft (153 m), a wing area of more than an acre (0.4 ha), twice the dimensions of the world's current largest aircraft An-225, and it can transport up to 1400 tons of cargo.

It has a long trans-oceanic range and can fly as low as 20 ft above the sea (span-based relative ground clearance of the order of $20/500 = 0.04$), but it is also able to fly at heights of 20,000 ft or higher. Intended for commercial and military operators who desire speed, worldwide range and high throughput. As indicated by John Skoupa, senior manager for strategic development for Boeing advanced lift and tankers "The Pelican stands as the only identified means by which the US army can achieve its deployment transformation goals in deploying one division in 5 days or five divisions in 30 days anywhere in the world". It can carry 17 M-1 main battle tanks on a single sortie.

Other applications are: as mother ship for unmanned vehicles, or as potential first-stage platform for piggybacking reusable space vehicles to appropriate launch altitude.

The (extreme) GE provides larger range and efficiency. The "Pelican" is foreseen to fly 10,000 nautical miles over water with a payload of 1.5 million pounds. As flying in GE requires the latest flight control technology, the vehicle will be equipped with reliable systems providing precise, automatic altitude control and collision avoidance. It is worth mentioning that Pelican is a *deja vu* concept. In the late sixties, Boeing was conducting intensive developments of an anti-submarine GE vehicle named "Lowboy" configured as an airplane with low-mounted high-aspect-ratio wing. The Pelican has been offered by Boeing as part of a system solution that would include the C-17 Globe

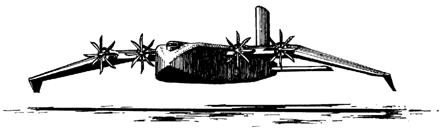

Fig. 27. Cargo plane-in-ground effect concept "Pelican" (Boeing).

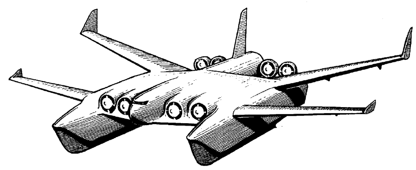

Fig. 29. Hydrofret 2 (concept, G. Gazuit and Y. Goupil).

master III transport, the CH-47 Chinook helicopter and the advanced theater transport.

3.5. Other projects and developments

3.5.1. Sea-Bus project (European Community, surface-piercing hydrofoil-controlled WIG effect configurations)

The Sea Bus (project, 1997–2000) is basically a large wing operating in GE just above the water surface which also features hydrofoils and a water-jet propulsion system [26], Fig. 28. The hydrofoils are positioned in a trimaran arrangement, and are connected to the air wing by vertical surface piercing struts. Separate V-shaped takeoff hydrofoils assist in generating lift force, thereby decreasing the takeoff speed at which the floating hulls of the vehicle rise from the water. The main purpose of the hulls is to provide buoyancy in floating operations at low speed in harbors and in takeoff and re-entry operations. Due to the large water density, the control of the vehicle by hydrofoils becomes more efficient in terms of shorter response time.

It was hoped that the longitudinal stability would be ensured by hydrofoils which implies redundancy of aerodynamic tail planes. It was required that the Sea-Bus should carry 800 passengers and 100 cars at a cruise speed of 100 knots over a distance of 850 km. One of the key problems is the cavitation occurring on the hydrofoils at speeds exceeding 40 knots.

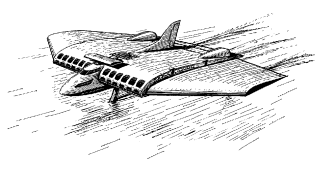

Fig. 28. European Sea Bus project.

3.5.2. Hydrofret concept

Proposed as a solution for the airport congestion problem, the Hydrofret (Hydrofreight) concept calls for extending the airfields to water surfaces. In fact, the authors of the concept, Gazuit and Goupil [27] advocate a specific formula for a seaplane, which features catamaran hull tandem wings large wing-like fuselage use of static (air cushion) and dynamic GE.

The concept is proposed in two versions. The first is a ram-wing catamaran complemented by a large-aspect-ratio lifting forward wing (side wings) and a highly mounted large-aspect-ratio tail plane. In the alternative version the tail wing is replaced by a large-aspect-ratio rear wing (side wings) forming a tandem with the forward wing, Fig. 29.

Deja vu: a seaplane design, combining a ram-wing catamaran hull with a wing of large aspect ratio (side wings), was proposed by R. Bartini in early 60s and is known as a Vertical-takeoff-Amphibia (VVA-14). The goal was to provide contact-free takeoff and landing of the seaplane.

The Hydrofret differs due to the second large-aspect-ratio wing element, highly mounted or located at the plane of the ram wing. A common gain in both versions with respect to a ram-wing GE machine is that the overall aspect ratio of the system is enlarged due to high-aspect-ratio wing elements. It appears that by properly adjusting relative position, pitch angle and areas of the large-aspect-ratio elements, one may provide static stability of the vehicle when flying close to the water surface. Additional reserve in this respect lies in special profiling of the ram wing in the longitudinal direction (S-shaping and similar measures).

However, there may occur stability problems in the transitional height range. Besides, while the highly mounted tail in the first version of the Hydrofret could have been seen as an unpleasant necessity for GE machines proper, it appears to be somewhat clumsy in free air flight which constitutes the main operational mode for the airplane.

3.5.3. Multihulls with aerodynamic unloading

A certain amount of work has been done on using the unloading effect of the presence of sea surface on high-speed catamarans. Doctors call such catamarans "ekranocats" [28].

Somewhat earlier a similar concept of a Ram Augmented Catamaran (RAC) was also proposed by Gallington [29] who found that (obviously) the most efficient power augmented craft should be touching water very little and cruise at high speeds. In fact the RAC concept is a tradeoff between increased drag of the side plates penetrating the waves and the loss of lift and propulsion associated with the lateral leakage of air.

As reported, Incat Tasmania has been conducting tests of a manned model high-speed craft, "the Wing", that employs the WIG effect concept to provide additional aerodynamic lift. Results of the model tests have shown speeds in excess of 60 knots. The test vessel is configured with three hulls (central hull forward, outer hulls aft) supporting a delta wing superstructure, Fig. 30.

A concept of a very fast "semi-WIG" wave-piercing trimaran (WPT) making use of aerodynamic unloading of the hulls was developed by Dubrovsky, Fig. 31.

The concept of what they call Air-Assisted Vessel Solutions has been explored in a joint effort by Effect Ships International (ESI) and SES Europe AS (SE). ESI claims to have patented Air Supported Vessel technology for both monohull and multihull vessels in 2002. They see it as an innovative approach to reduce hull resistance and improve performance—suitable for various naval and commercial applications.

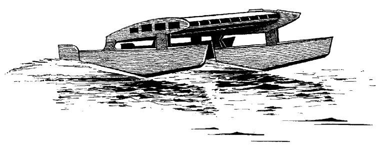

Fig. 30. A model of ekranocat tested in Australia.

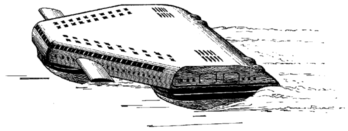

Fig. 31. Artist's view of a 100-knot "semi-WIG" WPT ferry designed to carry 600 passengers and 100 cars.

3.5.4. New Japanese WISE craft developments

A tendency of Japanese designs to have a simple flying wing configuration started by Kawasaki KAGs was confirmed in the μ-Sky vehicle series developed by Professor Syozo Kubo from Tottori University and built with support of Mitsubishi [30,31]. The μ-Sky 1 (Marine Slider) first flew in 1988. This 1-seater craft had a square platform and endplates, TOW of 295 kg and $L \times W \times H$ dimensions of $4.4\,\text{m} \times 3.5\,\text{m} \times 2\,\text{m}$. Powered by a 64 hp engine driving a 4-bladed fixed-pitch air propeller, the craft could develop a cruising speed of 82 km/h.

After the μ-Sky 1 vehicle a more sizable 2-seat μ-Sky 2 vehicle was developed and built by Mitsubishi under the supervision of Kubo [31], Fig. 32. While almost similar to the previous craft, it had certain distinctions: both air and water rudders, a wing structure made of aluminum pipes covered with cloth.

The project of a 8-seater "flying wing" type craft started in 1998 by S. Kubo and H. Akimoto (of Tottori University) with financial support from Fukushima Shipbuilding Ltd and additional funding (of the tests from April 2000 through April 2001) from Shimane Prefecture [32], Fig. 5.2.19. Takeoff weight 2.5 ton, dimensions $L \times B \times H = 12 \times 8.5 \times 3.7\,\text{m}$, cruising speed of 150 km/h, the expected range—over 350 km. Two water-cooled reciprocal engines rated 250 PS each, installed in the middle of the central body, drive two three-bladed propellers of 2 m diameter. The section of the main wing is Munk M6R2 for the upper side and CJ-5 for the lower side. The resulting camberline of the wing is S-shaped and the thickness is 9%. The center body of the ship (hull, cabin and root parts of the starboard and port halves of the main wing) is made of FRP strengthened by aluminum pipes. It has a step on the bottom and the rudder near the trailing edge. Outer wings and tail unit are constructed from aluminum pipes and covered by cloth. The outer wings have endplates at the tips. The main wing does not have a flap. The horizontal tail represents a

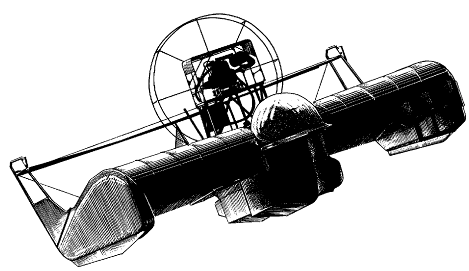

Fig. 32. μ-Sky 2 wing-in-surface effect (WISE) vehicle (S. Kubo, Mitsubishi).

stabilizer with elevator to adjust the angle of attack. The vehicle has two vertical fins with air rudders.

Japanese Canard WISES project:

The developers (from Tottori University, Japan) claim that a wing-tail configuration shows some defect in takeoff, whereas the proposed canard layout facilitates takeoff from rough seas [33]. They attempted to illustrate their idea by means of self-propelled model tests with 1.8 and 3.6 length models (Kaien (storm petrel)-1 and 2). They state that WISES should have seaworthiness over 3.0 m wave height for practical service in the seas around Japan. In the authors' opinion, the canard scheme allows to takeoff with high angle of incidence. In comparison, the wing-tail scheme does not allow large rotation angle without touching the water. They also think that PAR ceases to be an effective liftoff aid in rough seas because the impinged air leaks easily from under-the-wing. The canard-type WISES used by the authors has a forward mounted horizontal stabilizer (canard) and two propellers on it. The elevator on the canard controls the pitching moment of the ship and the deflection angle of the propeller wake. Vertical fins with air propellers are in the wake flow of the propellers. In the developers opinion, the merits of the concept are:

- high angle of attack position results in a high lift force,
- high-speed wake from the props prevents both the canard and the main wing from stalling, even in a high lift condition,
- the elevator and rudders are efficient even for small forward speed because they are in the propeller wake,
- propulsion systems always work in a spray-free region.

It is emphasized that the concept is better suited for large WISES. The main wing of Kaien-2 has a profile of NACA3409s (NACA3409 with modified camber line in rear part), whereas Kaien-1 had a profile of ClarkY. The lift-to-drag ratio in cruise was 6, i.e. somewhat lower than expected. Takeoff speed was 6 m/s and cruising speed was 9.5 m/s. The pitch angle in cruising was 4–5° and at takeoff—2.5–3.5°. In circular flight the mean roll angle was 5°. The maximum lift coefficient at takeoff (pitch up 15°) was 1.9, i.e. about 4 times larger than that in cruising.

They compared their preliminary design of a WISES for 140 passengers, displacement 56 tons, length 29.5 m, width 19.6 m, propulsion 3046 kW × 2 turboprop, maximum speed of 160 knots, with the Kawasaki Jetfoil. The former has a transportation capacity 1.5 times that of the Jetfoil.

3.5.5. *RotorWIG [34]*

Rotor WIGs are characterized by a large overhead rotor. The rotor allows for the third mode of locomotion, positioned between the hull and the wing. The rotor features tip weights that make up about half of the total weight of the rotor system. Before takeoff the rotor is over-rotated. Shortly after initiating the takeoff run, the pitch of the rotor blades is increased and, within seconds, the craft leaves out of the water. Suddenly freed from any water drag, the air propellers accelerate the craft swiftly to cruising speed and it is the wing that takes over the lift from the rotor. During cruise, the rotor is off-loaded and its rpm allowed to drop to lower the drag quite drastically. For landing, the rotor disc is held back to catch enough wind to act as an air break and increase its rpm. The energy in the over-rotated rotor is then spent to lower the craft softly on the waves during flare with little if any forward speed.

The HeliFerry [34]:

RotorWIGs can be configured in many different ways to fit different mission objectives. HeliFerry (HF) is a WIG version of HeliPlane, a twin pusher propeller rotorcraft of the size of a C-130 Lockheed transport plane and specifically designed around the Carter rotor system, Fig. 33. The HF is a double decked rotorWIG based on a very slender hull trimaran configuration. The low wing is of classic Lippisch, reverse delta design. The other specifications are: length—118 ft, rotor radius—150 ft, beam—70 ft, displacement—110,000 lbs, cruise speed—120 knots at sea state 3. The rotor system itself weighs 3 600 lbs, including the hub, pitch linkages and the tip weights, its rpm ranges from a

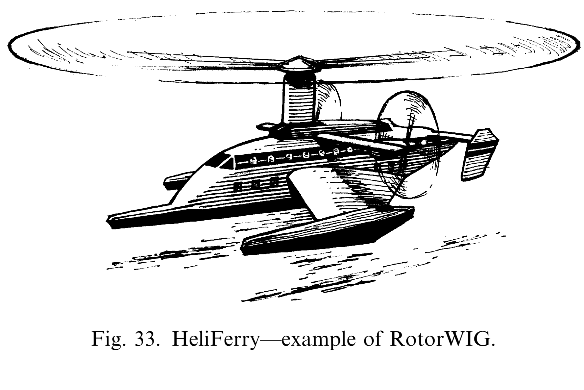

Fig. 33. HeliFerry—example of RotorWIG.

maximum in over-rotation of 125 to 85–100 required for full lift, to settle to 25 in cruise.

3.5.6. Korea WIG project [35]

Recently, it has been announced that the Korean government plans to invest by 2010 in the development of a large 300-ton WIG effect vehicle capable of carrying 100-ton payload at a height of 1–5 m above sea level. This WIG craft would have a length of 77 m, width of 65 m and would cruise at an average speed of 250 km/h. The plan is to use it as a next generation cargo ship to reach the neighboring countries or islands in South Korea. It could reach Qingdao, China from Inchon, South Korea in 3 h. In particular, it would be useful for fast delivery of fresh vegetables and fruits. Korea Ocean Research and Development Institute has already finished a successful test of a small four-seat WIG craft whose development started in 1995. A sketch of the Korean large WIG ship is presented in Fig. 34.

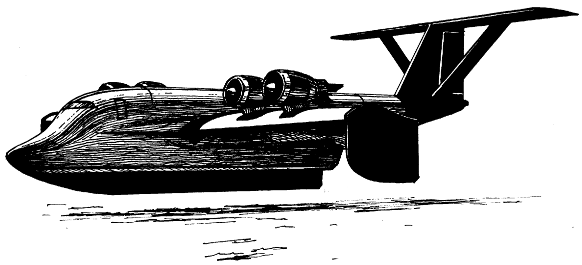

Fig. 34. Artist's impression of Korean large WIG ship.

4. Areas of application of WIG effect craft

Widely discussed, see Belavin [4], Volkov et al. [36] and Hooker [6], are such beneficial properties of ekranoplans as:

- cost effectiveness when properly designed and sized,
- high ride quality (low level of accelerations) in cruise mode,
- impressive seaworthiness in takeoff and landing and practically unlimited seaworthiness at cruise,
- safety of operation due to the effect of "binding" to the underlying surface and also because "...the airport is right beneath you..."
- amphibious capacity, i.e. ability to operate in GE over water, land, snow or ice surface,
- capacity of climbing an unprepared beach to embark/disembark passengers or carry out the maintenance of the vehicle,
- no need for airports or runways,
- no need for sealed cabins as required on stratospheric airplanes.

4.1. Civil applications

According to a preliminary analysis, as reported by Belavin [4], Volkov et al. [36] and Hooker [6], there exist encouraging prospects for developing commercial ekranoplans to carry passengers and/or cargo, to be used for tourism and leisure as well as for special purposes, such as search-and-rescue operations.

4.1.1. Search-and-rescue operations

Memories are still fresh about the tragedies that happened with the nuclear submarine "Komsomolets" on April 7, 1989 in the Norwegian Sea, and the nuclear submarine "Kursk" on August 12, 2000 in the Barents sea.

An analysis of existing means of rescue on water shows that surface ships are unable to come to the place of disaster quickly enough, while airplanes cannot perform effective rescue operations because the airplanes cannot land close to a sinking ship. Even most modern seaplanes have both lower payload and seaworthiness as compared to the ekranoplans. The GE search-and-rescue vehicle "Spasatel" is under construction at "Volga" plant in Nizhniy Novgorod.

"Spasatel", Fig. 35 which is based on the "Loon"-type ekranoplan, combines features of all known means of rescue on sea (search-and-rescue airplanes, helicopters, ships). Its cruising speed is expected to be in the range of 400–550 km/h in GE, and up to 750 km/h out of GE. Altitude when flying far from the underlying surface would be up to 7500 m, and about 500 m in searching mode. The vehicle can land and conduct rescue operations in waves up to 3.5 m. It is capable of loitering in rough seas with wave heights reaching 4 m. "Spasatel" has

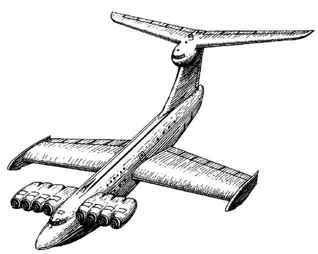

Fig. 35. Search-and-rescue ekranoplan "Spasatel".

a range of 3000 km, can operate autonomously for 5 days and is able to accommodate up to 500 people, see Denissov [37]. Before a decision todevelop "Spasatel" had been taken several experiments on the available missile carrier "Loon" have been performed to appraise the ekranoplan's capacity to serve as a rescue vehicle. These experiments showed that ekranoplans have some useful features justifying their use for rescue operations on the water. In particular, when drifting on water the vehicle is naturally brought to a position with its nose against the wind. As the vehicle's main wing is partially (with its aft part) immersed in the water, there forms a region of relatively calm water behind it. The upper side of the main wing can be used as a platform for embarkation of lifeboats and people from the water surface, Fig. 36.

The CHDB in Nizhniy Novgorod and the Ukrainian aviation enterprise "Antonov" jointly studied the possibility of developing a unique large search-and-rescue system which combines the long-range and high-speed capability of a large airplane with the life-saving features of ekranoplans in the sea, Fig. 37.

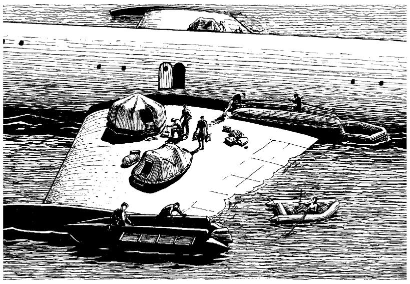

Fig. 36. Artist's impression of rescue operations with ekranoplan.

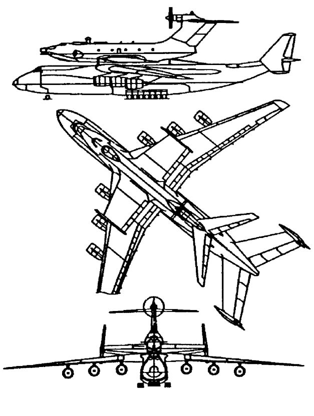

Fig. 37. A search-and-rescue complex combining the "Mria" and "Orlyonok" (Project).

The system implies that a search-and-rescue variant of "Orlyonok" with improved seaworthiness and special medical equipment is mounted on the back of the mammoth airplane AN-225 "Mria" to be transported to the place of disaster at a speed of 700 km/h. Upon arrival at the place of emergency the ekranoplan takes-off from AN-225, descends and lands on the water surface to turn into a seagoing rescue vessel. Note that due to the considerable strength of its structure the ekranoplan can land in rough seas, which is dangerous for seaplanes.

4.1.2. Global Sea Rescue System [38]

There is a worldwide concern to develop effective rescue measures on the high seas. Experience shows that it is very difficult if not impossible to provide timely aid at wreckages and ecological disasters at sea. Use of seaplanes is often limited because of unfavorable meteorological conditions, whereas use of helicopters is restricted to coastal areas. Until now, the main means of rescue (salvage) on water has been ships finding themselves accidentally near the disaster area and hardly suitable for this purpose.

A global sea rescue system is proposed, comprising 50 heavy weight ekranoplans, basing in 12 selected focal base-ports throughout the world. Each ekranoplan of the system is designed to have high takeoff/touchdown seaworthiness, corresponding to sea state 5 and enabling its operation on the open sea during 95% of the time year around. The cruise speed of each ekranoplan of the system is 400–500 km/h and the radius of operation constitutes 3000–4000 km. The vehicle can loiter for a long time upon the sea surface when seaborne at a speed of 15 knots. The rescue vehicle is supposed to bring to the place of disaster a wide array of rescue means including rafts and self-propelled cutters and, possibly, helicopters and bathysphere.

4.1.3. Horizontal launch of the aerospace plane

According to the project developed jointly by Musashi and Tokyo Institutes of Technology [39,40], an unmanned self-propelled ekranoplan is supposed to carry, accelerate to almost half sound speed and launch a 600-ton rocket plane to a low earth orbit (horizontal launch), see Fig. 38.

Launching useful payloads into low earth orbit and expanding the functional capacity of the aerospace transport systems is one of the major tasks of the developers of new space projects for the 21st century.

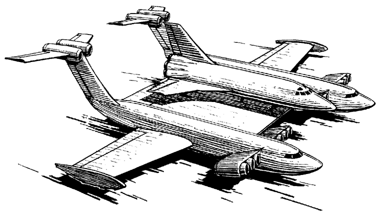

Fig. 38. Ekranoplan-rocket plane horizontal launch.

4.1.4. Other civil applications

Other potential special areas are the replacement of crews of fishing vessels, geophysical surveys, express delivery of mail and parcels over the ocean; coast guard and customs control operations. Ekranoplans of moderate sizes can be used to service coastal waters and to support transportation systems of archipelagos, carrying passengers and tropical fruits, fresh fish, etc. Similar considerations can be found in Kubo [41].

As per Hooker, the ultra-large vehicles of "Wingship" type offer many commercial possibilities, such as

- transportation of non-standard commercial payloads of large sizes and weights,
- search-and-rescue operations of large scale
- transportation of perishable goods in quantity throughout the world,
- high-speed luxury transportation,
- rapid response to international market fluctuations.

4.2. Naval applications

Analysis of known projects and future naval applications have confirmed that the above listed properties of ekranoplans together with their high surprise factor due to speed, low radar visibility, sea keeping capability, payload fraction comparable to similar size ships, dash speed feature and capacity to loiter afloat in the open ocean make them perfect multi-mission weapons platforms which can be deployed forward and operate from tenders, see Belavin [4], Sommer [42].

Naval ekranoplans can be used as strike warfare weapons against land and seaborne targets, launch platforms for tactical and strategic cruise missiles, aircraft carriers and amphibious assault transport vehicles. Easy alighting at moderate sea states makes it possible to utilize ekranoplans as anti-submarine warfare planes capable of effectively deploying hydrophones or towed arrays. They can also be used in a wide variety of reconnaissance and transport roles. WIG effect vehicles could adapt themselves to an operational concept of anchorages all over the world to maintain a forward posture.

4.2.1. Anti-surface warfare

Sustained sea-level operations of ekranoplans would reduce the horizon-limited detection ranges of defending airborne early warning systems, significantly reducing warning time. If the defender has no airborne early warning assets, mast height ship radars would not see the ekranoplan until it almost reached its target.

Back in 1966 the company "Grumman" developed a project of a 300-ton WIG effect missile carrier configured as a flying wing with in-flight variable geometry, the latter being achieved due to a peculiar design of endplate floats [4]. This project is shown schematically in Fig. 39.

Another example of a missile carrying strike ekranoplan is "Loon" with 6 dorsally mounted "Mosquito"-type missiles.

From operational and tactical viewpoints, the ekranoplan has incontestable advantages versus any other missile-carrying platform, in particular

- ekranoplan speeds exceed by an order of magnitude those of conventional surface ships. Unlike aircraft, the ekranoplan is not tied to airports or aircraft carriers and can be dispersively based in any coastal area,
- unlike aircraft, the ekranoplan is less visible, flies in immediate proximity to the water surface, and has large combat payloads (60 tons for the "Loon"). Due to its additional capability to conduct flight operations far from the underlying surface, the ekranoplan can perform self-targeting for larger ranges.

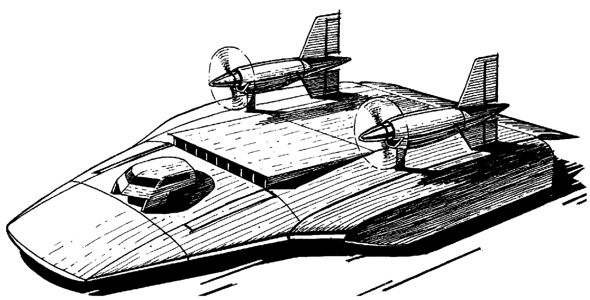

Fig. 39. Missile WIG vehicle developed by "Grumman" (Project).

4.2.2. Anti-submarine warfare

The ekranoplan would be an effective platform for anti-submarine warfare (ASW), being capable to detect, localize and destroy submarines at long ranges from their base. Its significant payload capability would allow it to carry numerous sonobuoys, torpedoes and mines. The ekranoplan could operate in a sprint-drift mode, alighting only to dip its sonar. In this case the search productivity exceeds that of any surface ship. In the late sixties Boeing is known to have developed an anti-submarine WIG effect vehicle named "Lowboy" configured as an airplane with low mounted wing, see Fig. 40.

Some estimates have been published stating that a 900-ton ekranoplan could carry a powerful low-frequency dipping sonar, sonobuoys, heavy anti-submarine weapons, self-defense weapons and sensors, have a dash speed of 400 knots and a mission endurance of 5 days, assuming 50% loiter operations.

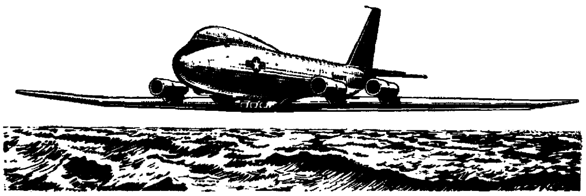

Fig. 40. Anti-submarine WIG vehicle "Lowboy".

4.2.3. Amphibious warfare

The speed, payload and low-altitude cruising capabilities of the WIG would enable devastating surprise assaults. It has also been noted by the analysts that the WIGs could have reached the Falkland Islands from Britain in hours versus the days it took surface forces to arrive during the conflict. The major difficulty with PAR-WIG amphibious operations is the actual landing of men and equipment. Since reduced structural weight is a key factor enabling efficient WIG flight, the vehicle cannot be reinforced to allow beaching without deterioration of its cruise performance.

An example of an amphibious assault craft is the Russian ekranoplan "Orlyonok". Whereas the "Caspian Sea Monster", notwithstanding such a threatening nickname, was not a combat vehicle, but just a huge flying test bed, "Orlyonok" was the first ekranoplan, specially designed for military purposes. The vehicle with a combat load of 20 tons has a cargo compartment length 24 m, width 3.5 m and height 3.2 m. To enable the embarkation–disembarkation of cargos of large dimensions and heavy military vehicles (e.g. tanks and armored carriers), "Orlyonok" has a unique swing-away bow design.

Operational experience with these amphibious assault ekranoplans confirmed their anticipated tactical and technical features, demonstrated their high level of safety and provides valuable information on their basing and maintenance.

4.2.4. Sea lift

Ekranoplans are expected to be quite effective in providing a sealift function. However, as shown by some estimates, in order to reliably brave high sea states, a trans-oceanic WIG would need to be very large, at least 900 gross weight tons. Even so it is estimated that one such WIG could deliver more cargo farther than three 300-ton C-5 aircraft-and do this while using 60% less fuel.

The WIG would fill the gap between conventional air-lifters and slow surface shipping. Unlike aircraft, the WIG would not be dependent upon overseas bases. Yet, unlike ships, WIG sea-lifters would be fast, require no escorts, and would be invulnerable to torpedoes and mines.

4.2.5. Nuclear warfare

The performance characteristics of the WIG would make it suitable as a launch platform for tactical and strategic cruise missiles. Its sea skimming cruise capability would allow it to exploit gaps in low-altitude radar coverage. Furthermore, its sea loiter feature would give it a flexibility not found in conventional strategic bombers. In fact, in a crisis, the WIGs could deploy to mid-ocean and alight on the surface to maximize their survivability.

The experts estimated that a 900-ton PAR-WIG carrying four TRIDENT missiles could be periodically relocated 100 miles or more to a new location every 4 h, while operating in an area 1000 miles from its home base for a period of up to 4 days, in sea state 3 conditions.

4.2.6. Reconnaissance and Patrol

Maybe, the weakest mission application for large WIGs would be in reconnaissance or patrol. The limiting horizon resulting from low-altitude operation would greatly reduce radar or signal intercept range, and therefore area coverage, to the point where it might not represent a cost-effective use of the platform. Even in the strike warfare posture against ships, WIGs would require targeting information from other platforms.

4.2.7. "Wingship" naval missions

Due to its very large payload of 1725 tons, the Aerocon's "Wingship" is expected to be able to provide significant military response capabilities. The "Wingship" was designed to carry 2000 troops and 1200 tons of equipment and supplies. This capability enables the rapid deployment of military units to any location in the world in a day or two. As pointed out by Hooker, the value of such early arrival can mean a significant reduction in the force required to achieve the same goal. The design payload of the "Wingship" is of mixed character and implies low- and high-density items. A representative example of the vehicle's payload includes: 32 attack helicopters, 20 main battle tanks, 305 105-mm Howitzers, 2000 troops and 1200 tons of equipment and supplies. To a large extent, the craft's design presents the opportunity to form new, restructured, more-effective marine forces. These forces would not be restricted to be lightly armored but could be more heavily armored units capable of deployment anywhere in a couple of days anywhere in the world. This would enhance possibilities for force projections throughout the world and increase available options for a given situation. Even the fact that such units exist would greatly contribute to regional stability throughout the world.

The "Wingship" may also provide a credible long range, long loiter ASW capability. Its large payload would increase both the amount and quantity of corresponding equipment and would permit the vehicle to remain on station as a rapid response ASW platform throughout the world's oceans. Since the volume and weight restrictions would be significantly raised, the technologies not available to airborne ASW platforms may now become accessible on the "Wingship". Military use of the "Wingship" would permit the development of next generations systems with less restrictions on size and weight. For example, the current theater missile systems are designed to be airlifted by the existing military airlift aircraft of the C-141 or C-130 type. In the Persian Gulf War, over 400 planeloads were required to deliver the limited Patriot capability that was employed during the conflict. With enhanced theater missile defense systems and a "Wingship" capability, a major improvement in missile defense capability would be available with far fewer plane loads delivered and at a reduced cost. Additionally, the rapid response feature of the "Wingship" would serve to reduce logical re-supply planning in any conflict. High speed and load carrying capability reduces the need to plan far ahead to ensure adequate supplies in any conflict. This would result in more flexible military responses to rapidly changing military situations.

5. Classification of WIG effect craft and some design parameters

5.1. Classification of WIG effect craft

5.1.1. By aerodynamic configuration

The wish to develop vehicles that exploit the GE and still have satisfactory longitudinal stability, has given birth to different aerodynamic configurations. In fact, the differences in configurations depend on the method of satisfying the longitudinal stability requirements (as per Irodov [43], for a statically stable WIG effect vehicle the center in height should be located upstream of that in pitch). The basic configurations are as follows.

5.1.1.1. Tandem configuration. The tandem configuration resolves the problem of stability by adjusting design pitch angles and the geometry of the fore and aft wing elements. This approach allows shifting the aerodynamic centers in a proper way for stability, while using wing profiles with maximum capacity to exploit the GE. The first tandem scheme self-propelled model was the 3-ton SM-1 launched in 1960, (see [12,13]). Although stable in a certain range of height-pitch parameters the model had a high takeoff speed and a "rigidity" of flight. Beside, the range in height of the motion stability turned out to be too narrow. The tandem scheme has been successfully used by Jörg (Germany) who developed this configuration for many years and built most of the tandem scheme craft (Tandem Aerofoil Boat—TAB) in the world [9].

The advantages of the tandem configuration are: simple construction, simple tuning of the configuration to secure a given static stability margin, effective one-channel (throttle) control, small span, i.e. length-to-beam ratio more similar to ships.

The main *disadvantage* of this scheme is that it operates only in GE with static stability margin very sensitive to the combination of pitch angle and ground clearance. For vehicles of small size the maximum operational height is small and seaworthiness is limited.

5.1.1.2. Airplane-type wing-tail configuration. The airplane-type configuration features a large main wing moving close to the ground and a horizontal tail plane mounted on a vertical stabilizer outside the influence of the GE thus shifting the center of pitch downstream. The airplane scheme emerged from the Russian R&D and construction work resulting in the creation of large ekranoplans of the first generation. Representatives of this scheme are "KM", "Orlyonok", "Loon" and "Strizh" (see [12,44]).

The main *advantages* of this configuration are: large range of heights and height–pitch combinations for which the vehicle sustains stable flight (hence a capability to perform an emergency "dynamic jump"), possibility to "hop" and provide banking necessary for efficient turning maneuvers, possibility to efficiently apply power augmentation at takeoff.

Large wing loadings leading to high-speed (this counterbalances the loss of the transport productivity due to low payload fraction).

The *disadvantages* are: very large weight penalty for having a high-mounted sufficiently large tail unit (up to 50% of the area of the main wing), which contributes only insignificantly to the lifting capacity of the craft while adding additional viscous drag, relatively low lift-to-drag ratios (economic efficiencies) due to the large non-lifting area fraction as compared to high lift-to-drag ratio of the isolated main wing; large structural weight and, consequently, large empty weight fraction.

The special case of an airplane (wing-tail) configuration is the Lippisch aerodynamic configuration featuring the main wing of a reverse delta planform and a relatively small tail unit [45]. The Lippisch idea of using reverse delta wing for the GE application can be interpreted as a (rather successful) attempt to restrict the longitudinal shifting of the center of pressure of the vehicle in response to variation of height. The latter effect is due to a linear decrease of the local chord of the main wing from the root chord section toward the tips. This configuration was employed in Lippisch vehicles proper (X-112, X-113, X-114 [46]), its derivatives developed by Hanno Fischer (Airfish craft family [19]) and also in some vehicles developed in other countries (Eska in the USSR, the XTW craft family in the People's Republic of China, etc.)

The advantages associated with the Lippisch-type craft are: high lift-to-drag ratio (around 25 for X-113), large range of heights and pitch angle of stable flight, capability to perform "dynamic jump" and efficient turning (due to "hop-up" capacity). The aforementioned advantages are similar to what was said before about the aircraft configuration. However, the high lift-to-drag efficiency is a specific feature of the Lippisch configuration. Specific disadvantage of the original Lippisch-type vehicles is their overpowering due to inefficient takeoff aids and the absence of power augmentation.

5.1.1.3. Flying wing configuration. The "flying wing" configuration is characterized by remarkably reduced non-lifting components, and a very small (or absent) horizontal tail. Here the tendency is seen to convert the whole craft into a lifting surface, resolving the problem of longitudinal stability by special profiling of the lower side of the wing or/and by making use of an automatic stabilization/damping system.

The "tailless" configuration of this type was proposed by Alexeev in the 70s [14] However, it was difficult to implement his ideas at that time and the scheme then was abandoned. Examples of "flying wing"-type vehicles are: "Amphistar-Aquaglide" (Russia) and, recently a WISE vehicle under testing in Japan. Both of these crafts have natural stability due to smart profiling of the wing section. Formally, some other vehicles can be assigned to this type (e.g. KAG-3, Japan) although they do not have the "flying wing"-type stability characteristics.

Advantages of the scheme are: efficient utilization of the vehicle to take maximum advantage of GE; low empty weight fractions, especially for vehicles of small aspect ratio.

Disadvantages of this configuration are: supposedly low range of height–pitch combinations to achieve longitudinal stability (without the use of automatic control systems), relatively low operational flight heights, additional difficulties in providing structural integrity of a water-based all-wing vehicle; inefficient use of flaps which (additionally) may deteriorate the static stability of motion when employed improperly.

5.1.1.4. Composite wing configuration. The "composite wing" configuration [14] seeks to combine the advantages of the airplane configuration and the "flying wing" configuration, thus achieving high takeoff efficiency when using power augmentation. A "normal" composite wing has a central wing of small aspect ratio (centroplan) with endplates and side wings of high aspect ratio. It employs the idea of profiling the lower side of the main wing to reduce the tail unit. The overall aspect ratio of the "composite wing" (4–5) exceeds that of the main wing of the vehicles of the first generation (2–3) and is by far larger than that of the tandem configuration as well as that of the existing "flying wings" (less than 1.5). The latter property results in much higher lift-to-drag ratios and, in combination with S-shaping of the wing sections provides higher efficiency and range. The small aspect ratio of the centroplan provides maximization of the efficiency of the power-augmented takeoff. An example of the vehicle based on the "composite wing" scheme is the MPE (Marine Passenger Ekranoplan) scaled series, e.g. the 450-passenger 400-ton ekranoplan MPE [12,14] has a reduced tail area of about 27% of the main wing, and increased range of 3000 km.

5.1.2. By altitude range: A, B and C types (IMO classification)

The ongoing difficult effort to obtain certification of WIG effect vehicles by the certification agencies and, in the long run, acceptance by the general public resulted so far in a certification of this craft based on the formal division of competence and responsibility between the IMO and International Commercial Aviation Organization (ICAO) [47]. For the time being the vehicles are divided into A, B or C types. According to this grouping, the vehicle belongs to A type if it is designed to operate only in (attached) GE mode (competence of IMO). The vehicles able not only to fly in GE but being capable of performing a temporary "dynamic jump" bringing them out of GE are ascribed to group B (joint authority of IMO and ICAO). Finally, the craft designed to operate both in and out of GE belong to group C (authority of ICAO).

5.1.3. By physics of the GE phenomena

One of the difficulties of defining spheres of competence of the IMO and ICAO, in particular as regards the A and B types, consists in finding reasonable definition of the absolute height of the "GE" zone. Some definitions introduced as of today are based on an assumption that the GE "works" starting from a certain relative ground clearance (e.g. 50% of the chord) and reporting the size (length of the chord) of the vehicle. However, as indicated in [1] and discussed in other works, e.g. [48], for a given size of the vehicle, the manifestation of the GE depends on its configuration and ratio of lateral and longitudinal dimensions. Rozhdestvensky [1] introduced notions of *chord-dominated (CDGE)* and *span-dominated (SDGE)* GEs. These notions reflect different physics of CDGE and SDGE. In the first case the wing responds to smaller ground clearances by flow stagnation under the wing, and subsequent growth of both lift and drag coefficients resulting eventually (for properly designed craft) in an enhanced lift-to-drag ratio. In the second case the GE reveals itself in reduced induced drag and enhanced lift, this combined effect finally also leading to increased lift-to-drag ratio. Therefore, it seems more appropriate to introduce a physical definition of the GE zone (in a way similar to the definition of the boundary layer thickness in the Prandtl theory). For example, the GE zone for a vehicle to be certified by the authorized societies can be defined as a distance from the (flat) ground below where the lift force has a (say) 30% increase as compared to the out-of-GE case for the same vehicle. Within this definition, use of the similarity theory allows one to determine the GE zone through model experiments and prescribed absolute dimensions of the craft long before construction of the scaled models and full-scale prototypes.

5.2. Some design parameters

The efficiency of WIG vehicles in terms of their range, fuel consumption, capacity to takeoff from water, ride quality when flying over waves and durability of structure is dependent upon the design wing loading $w = M/S$ and a density factor which can be defined as $\mu_f = M/S^{3/2}$, where M is the mass of the craft and S represents the wing's reference area. Figs. 41 and 42 show trends in behavior of the wing loading and density factors for existing and concept ekranoplans.

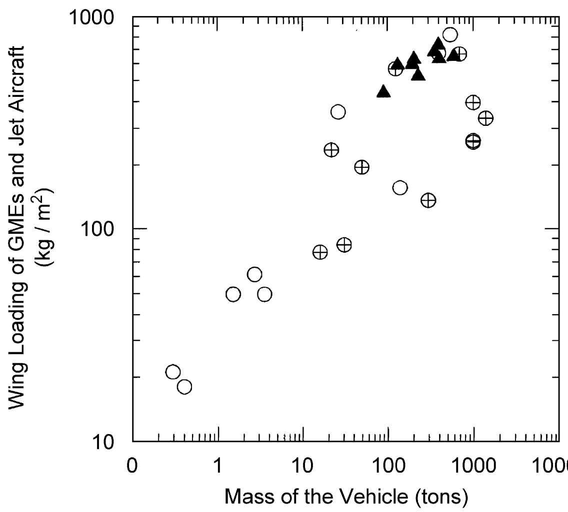

Fig. 41. Wing loading of wing-in-ground effect craft versus mass of the vehicle (circles—existing craft, crossed circles—WIG concepts, triangles—jet aircraft).

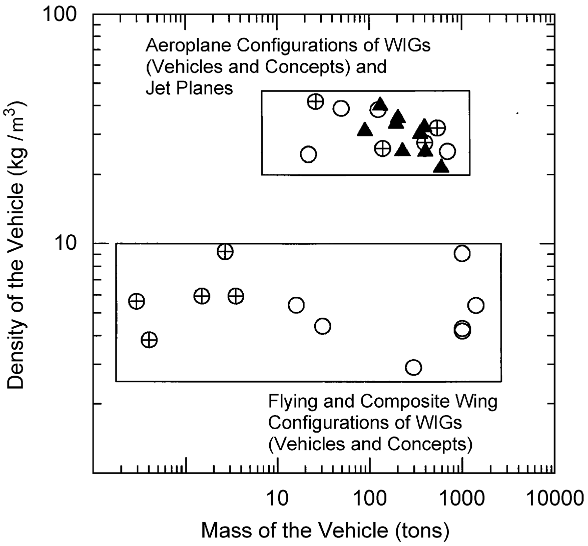

Fig. 42. Density factor of wing-in-ground effect craft and jet aircraft versus mass of the vehicle (crossed circles—existing WIGs, circles—WIG concepts, triangles—jet aircraft).

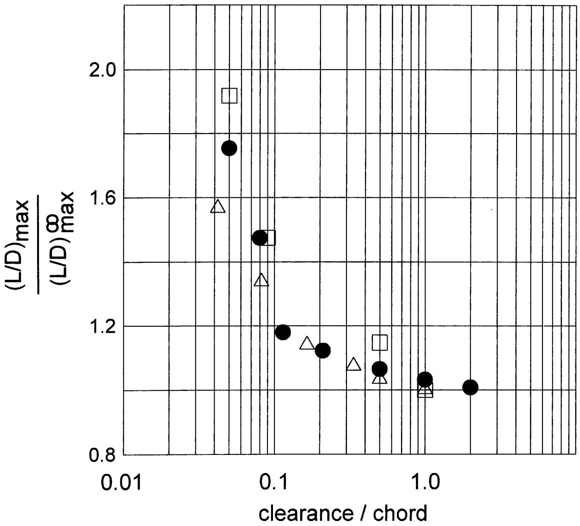

Fig. 43. Lift-to-drag ratio of a rectangular wing versus relative ground clearance ($\lambda = 2$, different symbols correspond to different relative thickness).

Plotted on the same graphs is aircraft data. Fig. 42 shows that the magnitude of the density factor significantly depends on the aerodynamic configuration of the vehicle.

As seen from the figure, the WIG effect vehicles of flying wing and composite wing configurations tend to have much lower density than the WIGs of airplane configuration and jet planes. This result shows that by adopting the novel aerodynamic configurations one can hope to reduce the penalties of the square-cube law which predicts an inevitable growth of the empty weight fraction with increase of the dimensions of the vehicle.

6. Aerodynamic aspects

6.1. Lift, drag and their ratio

For a properly designed lifting surface, the effect of the ground brings about augmentation of *lift* for smaller ground clearances, Fig. 43. Wing profiles with an almost flat lower surface (classical examples are Clark-Y and NACA 4412) produce optimum GE. Profiling of the foil for better longitudinal static stability usually results in lower lift coefficients which is not necessarily bad for cruise flight. For a given wing area the lift is larger for a larger aspect ratio wing. Flaps are not as efficient in GE as they are out-of-ground effect. The drag is mostly determined by its induced vortex drag component and it depends on the reciprocal relationship of chord, span and ground clearance, etc. Experiments and theory (including CFD analysis) show that, for a fixed pitch angle, in some cases (chord-dominated GE) the drag increases as the wing moves closer to the ground. In other cases (span-dominated GE) the drag decreases with decreasing ground clearance. In all cases, for a properly designed lifting system the lift-to-drag ratio tends to increase with decrease of the ground clearance.

Also, in all cases for a properly designed lifting surface the drag decreases with decreasing ground clearance for constant lift. The fact that near the ground the lift-to-drag ratio increases both with increase of the aspect ratio and decrease of the ground clearance provides more flexibility in selecting optimal design solutions than for the conventional airplane.

6.2. Influence of geometry and aerodynamic configuration

The lift-to-drag ratio can be quite large for an isolated WIG effect, but it drops significantly when the wing constitutes part of the integrated vehicle. The resulting loss of aerodynamic efficiency is especially remarkable for a vehicle of airplane configuration. As per Kirillovikh [11] the lift-to-drag ratio of a wing of aspect ratio 2–3 flying at a relative ground clearance of the order of 20% of the chord would be around 35–45, i.e. quite acceptable for creating an efficient transport platform. Upon integration of the vehicle (of airplane configuration), the losses of lift-to-drag ratio occur due to presence of the hull (40%) and pylons (15%) holding PAR engines and the (non-lifting) tail (5%), Fig. 44. Eventually, the resulting lift-to-drag ratio may drop almost 65%, i.e. in this example 12–16.

WIGs of the first generation have quite a large horizontal stabilizer needed to trim out the pitching moments experienced in GE, Fig. 45. While only negligibly contributing to the lifting capacity of the craft, use of the tail planes results in additional weight and drag.

As in the out-of-ground effect case the enhancement of the aerodynamic efficiency is due to the suction force at the leading edge. The available test and theoretical data show that leading edge flow separation becomes more probable in GE. Hence more attention should be paid to a thorough profiling of wing sections of the WIG effect vehicle. Some interesting comparative estimates of the maximum lift-to-drag ratio and the corresponding optimal design lift coefficient can be obtained on the basis of EGE theory [3]. In particular, this analysis shows that the more one gains in aerodynamic efficiency by flying closer to the ground, the smaller should be the design cruise speed of the vehicle. Secondly, going for a larger range entails a certain loss in lift-to-drag ratio compared to its maximum possible value. The said loss is of the order of 15%. It is interesting to discuss the maximum lift coefficient which can be realized for a WIG effect. The larger this coefficient the more efficient is the process of taking off, the smaller is the speed of detachment from water, with subsequent reduction of the weight fraction. Whereas out-of-ground effect

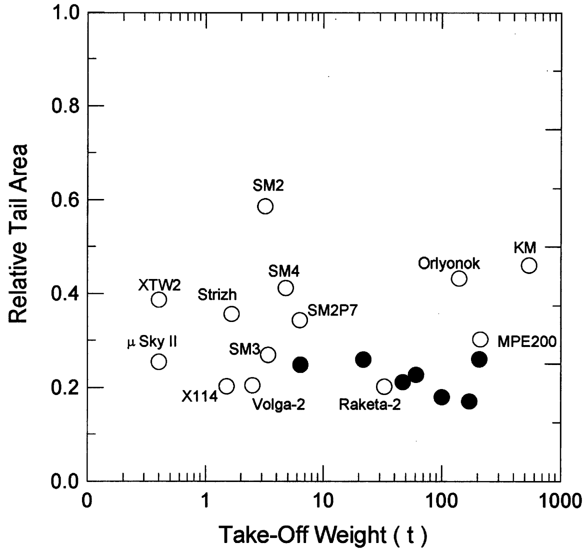

Fig. 45. Relative tail area of some wing-in-ground effect vehicles.

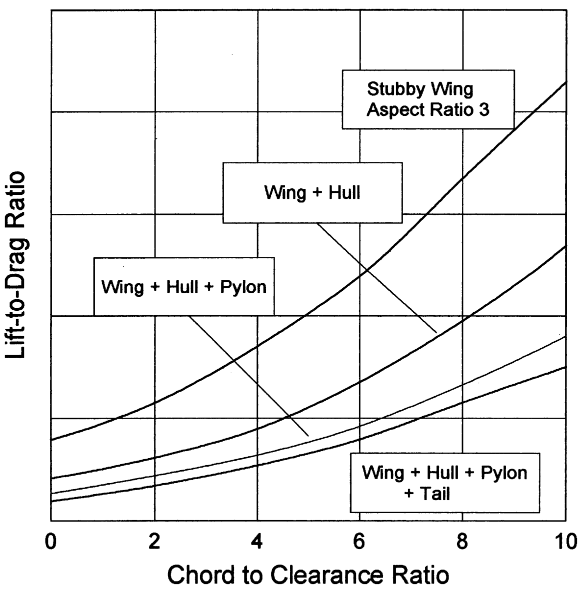

Fig. 44. Lift-to-drag ratio of wing-in-ground effect vehicles of different configurations.

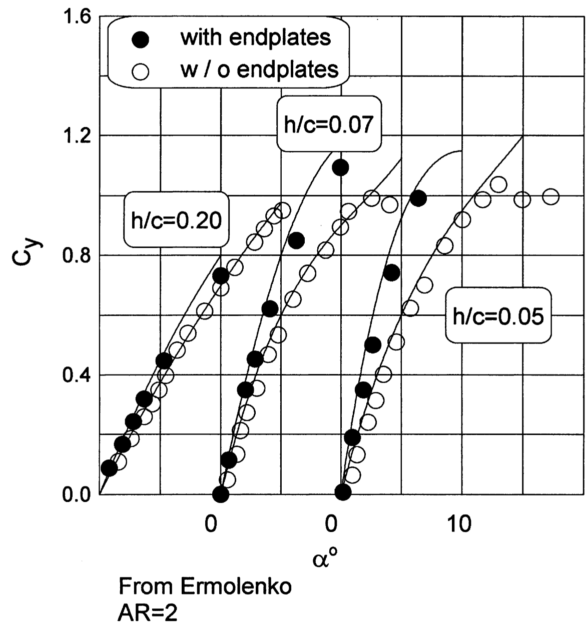

Fig. 46. Influence of endplates upon lift coefficient of rectangular wing of aspect ratio for different ground clearances.

of the maximum lift coefficient for the best transport airplanes is reported to be of the order of 2 using Fowler flaps, the maximum lift coefficient of the WIG effect is of the order of 1.6. The associated challenge consists of reducing the cruise lift coefficient, thereby extending the range and increasing the cruise speed of the vehicle for a given wing loading. Ref. [49] provides some data on the takeoff and cruise coefficients of some WIG effect vehicles.

6.3. Influence of endplates

The endplates are a specific feature of WIG effect craft as compared to the aircraft and seaplanes. Because the ram effect (chord-dominated GE) is due to the growth of the pressure difference below and above the vehicle (largely at the expense of the latter), the endplates become an effective means to hinder the leakage of the air from under the wing.

Both theory and tests demonstrate the following peculiarities of use of the endplates:

- Use of endplates leads to noticeable augmentation of the effective aspect ratio [50] thus making them "new players" in the design process of the WIG as compared to the aircraft (Fig. 46). There exist sufficient data prompting designers how to size endplates and position them chordwise.
- The smaller the aspect ratio the more efficient are endplates.
- Most of the endplate effect comes from their part on the bottom side of the wing.
- In EGE, as indicated by Rozhdestvensky [3], the endplates may be designed with moving (tiltable around an axis parallel to the center-plane, retractable) parts to provide control of the vehicle's static stability margin and motion.
- The endplates lead to shifting the optimal (design) lift coefficient toward larger magnitudes.

Yamane et al. conducted an investigation to see how the longitudinal position of the endplate influences the characteristics of the wing. Five investigated positions of the endplate with respect to the wing are represented in Figs. 47 and 48. The highest increase of the lift coefficient due to the endplate occurred for the endplate position EP00, that is when the center of the endplate coincided with the center of the wing. The nose down moment coefficient increased for successive shift of the endplate from the leading edge toward the trailing edge of the wing.

6.4. Influence of the planform and the aspect ratio

The present state of knowledge suggests that the optimal loading distribution of the main wing of the WIG tends to become parabolic, rather than elliptic. In

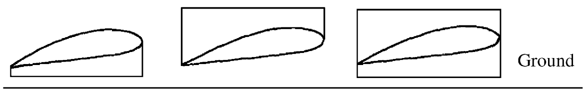

Fig. 47. Possible configurations of the endplate at the tip of the wing.

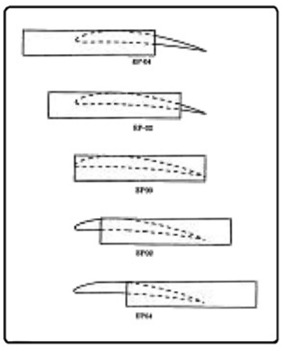

Fig. 48. Different longitudinal positions of endplates investigated by Yamane.

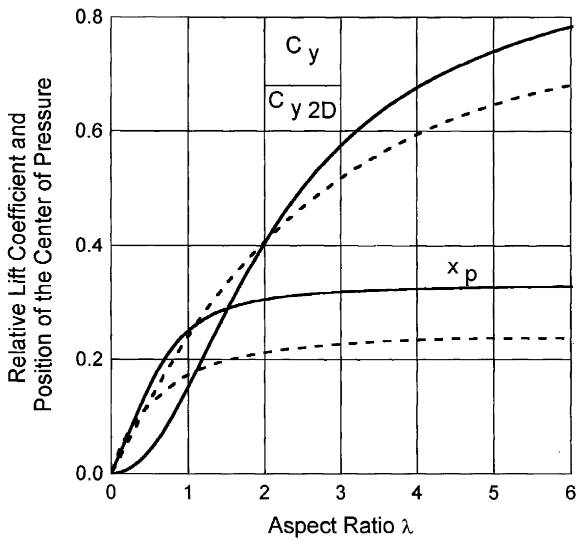

Fig. 49. Relative lift coefficient and position of the center of pressure for a rectangular wing versus aspect ratio in the extreme ground effect (continuous line) and out-of-ground effect (dashed line) cases.

terms of the optimal platform it suggests a parabolic planform for a wing of large aspect ratio, and, as found by Widnall, a semielliptic planform with straight trailing edge, for a wing of arbitrary aspect ratio [51].

Interesting comparisons can be made concerning the influence of aspect ratio upon lift coefficient in ground and out-of-ground effect on the basis of EGE theory, Fig. 49.

The aspect ratio affects the efficiency in a way similar to the out-of-GE case, i.e. the larger the better. However, sticking to smaller aspect ratios (with efficiency enhanced by endplates) pays back by decreased structural weight and conveniences associated with use of the marine transportation infrastructure.

6.5. *Influence of waves in cruising flight*

There are several major situations that need to be considered for the case of a WIG effect vehicle operating in a sea environment

- floating and drifting in waves,
- takeoff in waves,
- landing in waves,
- cruise flight over waves,
- occasional impact of the waves and, in exceptional case, of rogue waves upon the vehicle and its elements.

We will discuss herein only aerodynamic effects experienced by WIG effect vehicles operating in close proximity to the sea surface. The results of experiments and theoretical (computational) investigations of this kind of unsteady motion of a lifting system show that

- A wing flying in proximity of a wavy surface experiences an additional unsteady lift which changes periodically.
- The net wave-induced lift force for a wing with flat lower side, averaged over the wave period, is positive. The latter circumstance explains why the wing catapulted along such a wavy surface tends to climb. The effect under discussion is due to the nonlinearity of the GE phenomena whereby the average lift increment due to wave crests is somewhat larger than the lift decrement due to wave troughs.
- The amplitude of the wave-induced unsteady force depends on the ratio of the wave length to the chord of the wing. For practical Strouhal numbers, a reduction of this ratio results in a decreased amplitude, see Fig. 50.
- The wave-induced response of the vehicle depends on the vehicle's density, ground clearance and pitch angle, and, naturally, on the wave length as a fraction of the wing chord and on the wave amplitude.
- There exists for every vehicle and its design ground clearance a resonant wave which is longer for vehicles of high density, at larger relative ground clearance and smaller associated "spring" property, that is for a smaller derivative of the lift coefficient with respect to ground clearance. Because of their large density, large vehicles do not "notice" the aerodynamic influence of the waves unless they encounter waves of very large length.
- For the high Froude numbers at which the WIG vehicle is normally operating, there is no noticeable deformation of the water surface. It means that in this case the water surface behaves as if it were a solid wavy wall.
- More significant aerodynamic impact upon the wing may occur due to vertical gusts generated by orbital motion of the air particles excited by the wavy free surface. Research shows that this effect displays itself in proportion to the wave amplitude, magnitude of wind speed and difference in velocity of the vehicle and the wave.

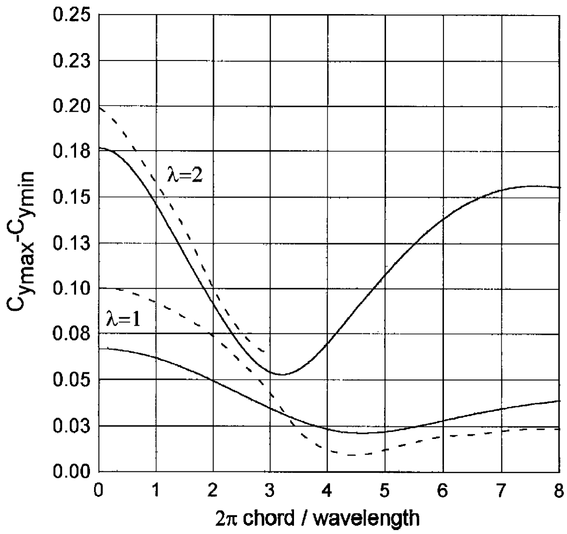

Fig. 50. Amplitude of unsteady lift coefficient versus relative wavelength.

In practice, roughness of the sea surface leads to lower efficiency of the vehicle because it has to increase the ground clearance in order to avoid contact with waves crests. On the other hand, a conclusion to draw is obvious: start design of the wing with specification of the required seaworthiness and conceive the craft large enough to retain sufficient lift-to-drag ratio. Some experimental and theoretical data on the influence of waves on the aerodynamics of WIG effect can be found in [52–56].

6.6. Compressibility effects

For large vehicles of high wing loading, i.e. advancing with very high cruising speeds, the compressibility of the air may have to be considered. Note that, for instance, for a cruising speed of 550 km/h (KM) the associated Mach number is 0.46. The effects of compressibility were investigated both experimentally and theoretically. But it can be stated that little is still known with regard to GE at high subsonic Mach numbers.

Application of the Glauert factor to account for the compressibility using linear as well as EGE theory [3] reveals more pronounced (at least for a wing with flat lower surface) effect of Mach number than for the identical wing out-of-ground effect. This can be explained using the concept of "equivalent" wing moving in the incompressible fluid at a smaller "equivalent" ground clearance, hence higher lift coefficient. The results obtained for lift-to-drag ratio are somewhat contradictory. There are some indications based on existing test data indicating that some improvements of the lift-to-drag ratio could be achieved at high subsonic Mach numbers [57], Fig. 51.

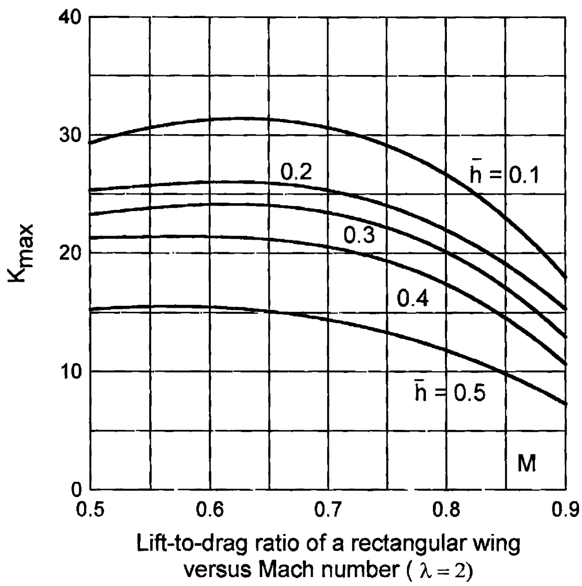

Fig. 51. Lift-to-drag ratio of a rectangular wing ($\lambda = 2$) versus Mach number.

The EGE theory, in its turn, predicts (for a flat wing) monotonous decrease of the efficiency with increasing Mach number.

6.7. Aero-elastic effects

Elasticity may become a consideration for vehicles of large dimensions as well as in the case of use of composite materials and fabric [12,57]. It should be accounted for in the structural design of ekranoplans as these vehicles have extensive and elastic lifting surfaces equipped with control surfaces and operated at high speeds in air and water. In principle, the problems of aero-elasticity are treated similarly to those of conventional aircraft, i.e. static aeroelasticity effects (reversal of control), flutter and dynamic response of the structure. One of the important problems of aero-elasticity of large vehicles with hydroskis is associated with dynamic stability of the system "hydroski device plus elastic ekranoplan" when the craft performs a transient motion with extended hydroski. In this case, in the course of takeoff and landing, at certain speeds an intensive oscillatory response can occur. It is accompanied by a high level of dynamic bending moments and overloads on the hull and a significant variation of the resistance forces in the shock-absorbing hydro-cylinders governing the extension and retraction of the hydroski. This process is characterized by a coupled elastic oscillations of the hull and dynamic deviations of the hydroski which occur with a frequency close to the first vertical bending mode of the hull.

In the analysis of the static aeroelasticity of ekranoplans, one should note that the bending and torsion stiffnesses of its structural sections are higher than those of conventional aircraft structures for the same mass and geometric dimensions. Although the cruising speeds of large ekranoplans were about 150 km/h below the estimated speed of flutter, the accumulated experience indicates that due to aero-elastic effects the lift-to-drag ratio of the craft may decrease substantially. Theoretical investigations of aero-elastic instability of wings in GE

(Buyvol and Ryabokon, Efremov, Rozhdestvensky, Lifenko and Rozhdestvensky) showed that (at least in EGE) both speeds of flutter and divergence diminish with decrease of relative ground clearance.

Special investigations are required to study the dynamic behavior of flexible lifting surfaces (PARAWIG). Simplified analysis of the latter effects has been performed in [3].

6.8. *Peculiarities of the aerodynamics of formation flight*

The wake systems generated by ekranoplans in formation flight may significantly influence the vehicle aerodynamics. Besyadovskiy [58] studied these effects for different relative positions of two vehicles. In particular, he explored the cases when the vehicles moved in the same and different vertical planes and had different relative flight heights. Some of the conclusions are:

- the leading ekranoplan experiences a certain decrease in lift coefficient and some diminution of static stability margin,
- in most of the cases one observes some augmentation of (static) stability of the following ekranoplan,
- the worst case may occur when the centerline of the following ekranoplan is in the same vertical plane as the side edge of the leading ekranoplan.

7. Mathematical modeling of aerodynamics

A rational approach to the design of any unconventional vehicle, for which the existing prototype data are restricted, should be based on an appropriate mathematical model, reflecting the essential features of the craft under consideration.

Ekranoplans can be viewed as such an unconventional type of superfast water transport, utilizing the favorable influence of the underlying surface (ground) upon its motion stability, lift-to-drag ratio and, consequently, on its economic efficiency, expressed in terms of fuel consumption and direct operating costs.

Today's remarkable growth of computing power combined with CFD (computational fluid dynamics) allows a quite accurate prediction of the aerodynamic behavior of any given configuration of WIG effect vehicles. A short survey of the corresponding numerical approaches and results obtained with Euler and Navier–Stokes solvers can be found in [3]. In spite of all known advantages of the CFD methods, there still exists a need for approximate engineering approaches allowing fast evaluation of the quality of the system, providing a simple explicit representation of the aerodynamic response and a plausible basis for design optimization. Such approaches often employ analytical (asymptotic) methods. A survey of asymptotic methods for the analysis of lifting flow problems in GE and a theory of the aerodynamics of EGE[1] is presented in the monograph "Aerodynamics of a Lifting System in Extreme Ground Effect" by K.V. Rozhdestvensky [3].

The first asymptotic approaches relevant to the (span-dominated) GE phenomena employed Prandtl's lifting line model and its mirror reflection, e.g. Wieselsberger [59], Serebriyskiy [60], etc. In this research, the distance of large-aspect-ratio wing from the ground was considered to be of the order of span, whereas the chord of the wing was assumed much smaller than both the span and the ground clearance.

Because the GE depends on the relative distances (h) of the wing from the underlying surface, it is reasonable to seek approximate solution of the corresponding flow problem in the form of an asymptotic expansion in terms of a small parameter related to h.

Some of the earlier approaches were based on asymptotic expansions with respect to a small parameter inversely proportional to the ground clearance. Keldysh and Lavrent''ev applied the parameter $1/h$ to treat the flow past a hydrofoil moving near a free surface. A similar expansion was used by Plotkin and Kennel [61] to obtain the lift coefficient of an arbitrary thin aerofoil in the presence of a ground plane, and by Plotkin and Dodbele [62] and Plotkin and Tan [63] to solve the flow problems for large-aspect-ratio wings and slender wings in motion near a solid flat wall.

It is obvious that an expansion in $1/h$ is appropriate at distances from the ground which are larger than the chord (or the span) of the wing. However, because WIG effect vehicles normally operate at distances below 25% of the chord (span), it is practical to introduce a small parameter

[1] In [3], the term *extreme ground effect* (*EGE*) is associated with relative distances from the ground less than 10%.

providing convergence of the solution series at distances less than the chord (span). Panchenkov [64] obtained asymptotic solutions of a set of lifting flow problems involving interfaces (free surface and solid wall) in terms of the parameter $\tau = \sqrt{1+4h^2} - 2h$ which allows to improve convergence of the series solution. One can see that τ tends to 1 when h goes to zero and tends to $1/4h$ when h tends to infinity.

Because WIG effect vehicles have maximum aerodynamic efficiency in very close proximity to the ground (i.e. at distances essentially less than the chord and/or the span) it is practical to use an asymptotic expansion of the flow problem solution around the limiting case $h = 0$. This can be done with use of the method of matched asymptotic expansions (MAE) and leads to *a theory of EGE*.

It turns out that for $h \to 0$ the mathematical description of the flow can be simplified. In particular, the 3-D flow problem acquires a 2-D description and the 2-D problem acquires a 1-D description. Physically, in the case of RAM wing, it means that close to the ground the major contributions to its aerodynamic characteristics come from the channel flow between the wing and the ground. Thus, one may speak of a *hydraulic nature* of (chord-dominated) GE.

Apparently, Strand etal. [65] were the first to indicate the channel flow nature of the highly constrained flow between the wing and the ground. They stressed the point that in the two-dimensional case the channel flow becomes one-dimensional. However, no method was presented then to determine the total amount of mass flow under the wing without solving the entire flow problem. It is interesting that the idea of using channel flow (hydraulic) theory to determine the increase of lift due to GE was also found in the notes of a famous German engineer Alexander Lippisch and was then published by his colleague Mr. Borst [66].

If there are no losses, the variation of pressure can be found for a two-dimensional wing based on a channel flow consideration using Bernoulli's law and the continuity equation. Requiring that the velocity and pressure at the wing traili ng edge equal the free stream values, one can easily obtain the following formulae for the pressure coefficient along the chord and the lift coefficient

$$C_p(x) = 1 - [h_0/h(x)]^2, \quad C_L = 1 - \int_0^1 \frac{h_0^2\,dx}{h^2(x)},$$

where $h(x)$ is a local clearance between the foil and the ground and h_0 is the trailing edge height. Lippisch notes that when applying these formulae, the trailing edge height h_0 should not be assumed to be equal to the geometric value, as the boundary layer builds up causing a reduction in the gap height. Thus, even for zero angle of attack when the bottom surface is parallel to the ground, there can be a lift increase due to ram. So, the same formulae can be used with both the local and the trailing edge clearance corrected for the (displacement) thickness of the boundary layer. A flow leakage occurs when there are gaps between the tips of the endplates and the ground. This flow leakage results in a corresponding reduction of the ram lift. In the theory of Lippisch, as exposed by Borst, the magnitude of the ram lift loss due to the endplate leakage was determined by finding the ram lift needed to achieve agreement with test data after introducing corrections into two-dimensional airfoil data.

The first MAE applications for lifting flows near the ground were introduced by Widnall and Barrows [67] in linear formulation, examples including a flat plate of infinite aspect ratio and a flat wing of semielliptic planform. Extension of the MAE approach to a linear unsteady flow case accounting for wing aspect ratio, flaps, endplates, slots and compressibility effects was carried out by Rozhdestvensky [44,56,68–79]. Beside the lift and moment coefficients, he calculated the induced drag coefficient for both steady and unsteady cases with full and partial realization of the leading edge suction force.

Kida and Miayi [80] applied the MAE approach to solve the flow problem for a non-planar wing of finite span in motion very close to the ground and for a jet-flapped WIG effect.

It should be mentioned that at very small relative ground clearances, even slight changes in geometry and kinematics of the lifting system may result in considerable perturbations in the channel flow under the wing and, therefore, in the aerodynamic response of the lifting system. Hence, the theory should account for nonlinear effects. For the case of the extreme (curved) GE in a compressible isentropic lifting flow, an unsteady, nonlinear, 3-D treatment of the problem was given by Rozhdestvensky [68]. The influence of waves on the underlying surface was studied for both the case of translational motion of the wing in a direction normal to the wave front and for an arbitrary course angle, respectively [74]. Later, a leading-order nonlinear formulation was developed by Tuck for two-dimensional (1980, unsteady [81]) and three-dimensional (1983, steady[82]) incompressible flows. Newman [83] was able to represent the channel flow beneath the lifting surface by a simple nonlinear solution in a cross-flow plane with appropriate conditions imposed at the trailing and leading (side) edges.

As indicated previously, due to the dominating influence of the flow between the lower surface of the wing and the ground upon the aerodynamics of lifting surfaces in EGE, the corresponding three-dimensional flow problem can be reduced to that in two dimensions in the planes parallel to the unperturbed position of the underlying surface. Thus, the EGE theory forms an interesting complement to Prandtl's lifting line theory and Jones'' slender body theory in which the flow fields are basically two-dimensional in the transverse and longitudinal planes, respectively.[2]

Further simplification can be introduced for a wing with endplates moving in close proximity to the ground. In this case, the flow description can be shown to be predominantly one-dimensional. A simple one-dimensional nonlinear mathematical model of the flow past a rectangular wing with small relative clearances under the tips of the endplates was derived and then validated experimentally by Gallington et al. [84]. This approach was based on an assumption that the (channel) flow parameters are independent of the chordwise coordinate and on the observation that the leaking flow escapes from under the tips of the endplates into the external region with atmospheric pressure. The author also assumed the occurrence of separation at the tips of the endplates.

Though very simple, Gallington's flow model agreed qualitatively with experiments and provided interesting similarity criteria. An important consequence of the introduction of this model from the theoretical viewpoint was that it helped to overcome a paradox of the infinite (logarithmic) increase of the flow velocity at the gap encountered by other researchers. One of the restrictions of Gallington's one-dimensional model ensues from the assumption of the constancy of the loading along the chord. As a consequence, the model cannot be used for the prediction of the longitudinal moment and characteristics of stability. Secondly, it is confined to the case of steady motion, whereas the analysis of the transient motion of WIG effect vehicles is of utmost importance. Rozhdestvensky [3,85] extended Gallington's nonlinear mathematical model of channel flow, taking into account the chordwise distribution of flow velocity (pressure) and introducing unsteady effects.

The aforementioned research effort is associated with chord-dominated EGE (RAM wing) in which one observes growth of pressure on the lower side of a properly designed WIG effect. In the case of span-dominated EGE, it is convenient to consider integral formulations. Rozhdestvensky [86] provided an analysis of the steady flow past a lifting line and a tandem, comprising two lifting lines, in the immediate proximity to the ground. In the former case, for a vanishing clearance-to-span ratio, he was able to reduce Prandtl's integro-differential equation to a simple ordinary differential equation for the spanwise loading distribution. In the latter case, a system of two integro-differential equations degenerates for vanishing relative (with respect to span) ground clearance into a corresponding system of ordinary differential equations of the second order. In both cases, the solution of the resulting differential equations, subject to conditions of zero loading at the tips of the wing, were obtained in analytical form.

The most complete account of the formulations and main results of EGE theory can be found in Rozhdestvensky [3]. Some of the main conclusions from there are listed below

- At small relative clearances, the effective aspect ratio is a function of three factors: geometric aspect ratio, ground clearance and gaps under the tips of the endplates. Thereby, the design solutions become remarkably diversified as compared to the out of GE case.
- The aerodynamics of the lifting system in EGE is dominated by the *channel flow* under the main wing(s). Hence, the aerodynamics, and especially the lifting capacity and longitudinal stability of the vehicle largely depend on the instantaneous geometry of the gap between the main wing and the underlying surface.
- EGE is a highly nonlinear phenomenon. Therefore, superposition of different effects is not possible. For example, the effects of thickness and curvature cannot be studied separately or added. The combined influence of thickness and curvature is largely defined in this case by the shape of the lower side of the wing. Nonlinearity

[2]This was first indicated by Widnall and Barrows [67].

also gives rise to non-zero components of the time-averaged vertical forces acting on the main lifting system when the vehicle performs an unsteady motion in immediate proximity to the ground. These non-zero lift contributions can be directed either toward the ground or upwards. For example, the motion of the main lifting wing with a flat lower surface over wavy ground at a positive pitch angle gives rise to a non-zero averaged lift increment.

- Influence of compressibility is more pronounced in GE than out of GE. In particular, for a subsonic flow past wings of moderate and large aspect ratio in close vicinity of the ground an increase of Mach number entails a larger increment of lift than that for the out-of-ground effect case. To understand how important it may be to account for compressibility when designing an ekranoplan, it is worthwhile to note that the cruise speed of KM constituted about 40% of the speed of sound at sea level. At larger speeds compressibility effects can become more dramatic with possible formation of shock waves.
- In EGE, the influence of the aspect ratio and unsteadiness of the flow upon the aerodynamics of the main wing are mostly caused by free vorticity (steady and unsteady) within the wing's planform.
- Similar to airplanes, optimum lift-to-drag ratio for an ekranoplan requires the realization of the suction force at the leading edge. Hence, the profiling of the leading edges of the lifting system designed to operate in EGE should be done very thoroughly. All available means of boundary layer control should be applied to avoid separation. It can be shown that when a wing approaches the ground the probability of occurrence of separation increases.
- Optimal design solutions in EGE differ qualitatively from corresponding airplane results. Whereas for an unbounded fluid the optimal spanwise loading distribution is known to be elliptic, for a lifting surface in EGE the *optimal loading becomes parabolic*. Correspondingly, the optimal geometry of the lifting system becomes different from the unbounded fluid case. For example, minimization of the induced drag of a large-aspect-ratio wing in EGE requires a parabolic rather than elliptic "twisting", i.e. spanwise distribution of the angle of attack.
- In EGE even a small blockage of the flow near the trailing edge leads to a noticeable reduction of the longitudinal static stability margin for foils whose lower sides are designed to enhance stability.

8. Stability of longitudinal motion

One of the major technical difficulties a developer of a WIG effect vehicle has to overcome is related to static and dynamic stability of motion and, in particular, the pitch stability. As in the case of the airplane, the subject of stability can be divided into static and dynamic stability.

> Static stability means that when a vehicle is disturbed from its equilibrium, it will tend to return to the state of equilibrium.

Essentially, the static stability is determined by the direction of forces and moments acting upon the vehicle right after application of perturbations.

> Dynamic stability implies, that following a disturbance an undamped vehicle will oscillate about the state of equilibrium, but eventually, the oscillations will die out and the vehicle returns to its steady state of equilibrium.

Whereas the *static stability can be evaluated* through assessment of the tendency of the vehicle to restore the initial state of equilibrium just after action of perturbations, in dynamic stability analysis one is concerned with the time history of the motion of the vehicle after it has been disturbed from its equilibrium point. As a matter of fact, the static stability does not necessarily imply the existence of dynamic stability. However, if the vehicle is dynamically stable it must be statically stable. The decay of the disturbance with time indicates that there is resistance to the motion, which can be associated with dissipation of energy (positive damping). If the energy is being added to the system, one deals with the case of negative damping. If the energy of the system were the same versus time, this would correspond to zero damping case. It is of interest both for the designer and for the operator of the vehicle to be able to measure the degree of dynamic stability. The degree of dynamic stability is normally specified by the time it takes a disturbance to be damped to half of its initial amplitude. Similarly, the measure of dynamic instability can be characterized as the time it takes for the initial amplitude of the disturbance to double. In the case of oscillatory response of the system to a perturbation, the frequency of the resulting perturbed motion is also quite important.

The problem of ensuring stability of the craft hindered many past developments. As referred to earlier, to ensure static longitudinal stability of his modified "Aerosledge No. 8". Kaario equipped the vehicle with stabilizing aft beams, which were supposed to slide along the snow and water surface. For the same reason, Troeng fixed a small hydrofoil at the rear part of his craft. To ensure static stability of his vehicle Weiland applied a tandem layout comprising two wings of high aspect ratio and a horizontal stabilizer with an elevator. However, as indicated earlier, the prototype vehicle "Small Weiland Craft" had a serious accident during the trials, supposedly due to instability [4].

It is known that in the mid-seventies, in spite of a considerable effort the famous Russian engineer Alexeev did not succeed in providing longitudinal stability for his prospective "flying wing" configuration. So far, only the airplane (wing-tail) configuration of the "Caspian Sea Monster"-type vehicles and the Lippisch inverse delta wing with negative dihedral and a tail have shown reliable levels of stability over a sufficiently wide range of pitch angles and ground clearances.

Research on WIG vehicles revealed significant peculiarities of their stability criteria as compared to aircraft, which normally operates out of GE, see [43,48,87].

Whereas the static stability of an airplane of any aerodynamic configuration in normal flying mode can be provided by an appropriate selection of the longitudinal position of the CG, the stability of a WIG vehicle can be provided only through appropriate design of the aerodynamic configuration.

Strong coupling between the aerodynamic configuration of WIG effect vehicles on one hand and flight stability and dynamics, on the other hand, was found as a typical and difficult problem of their design.

Before embarking upon a short survey of research work done in the field of static and dynamic stability of WIG vehicles, it is worthwhile to dwell upon peculiarities of their static stability using simple physical reasoning.

Let us start with a somewhat simpler case of an airplane in flight out of GE, and assume that the nose up aerodynamic moment around the CG is positive and the nose down moment is negative. Suppose that the airplane, flying in the state of equilibrium, suddenly encounters an upward gust resulting in increase of the angle of attack. To assess static stability in this case one would have to check what would be the response of the craft in terms of the aerodynamic pitching moment. If the system responds with a nose down pitching moment, restoring the state of equilibrium, the airplane would be classified as statically stable. If, on the other hand, the resulting pitching moment tends to further deflect the airplane upwards, thereby increasing the angle of attack still more, the craft's behavior would correspond to an unstable equilibrium point. This simple analysis leads to an important conclusion:

> To have static longitudinal stability the aircraft should respond by a negative increment of the pitching moment to a positive increment of the angle of attack and vice versa.

Because augmentation of the angle of attack normally brings about augmentation of lift, the latter conclusion can be formulated alternatively as:

> To have static longitudinal stability the aircraft should respond by a negative increment of the pitching moment to a positive increment of the lift.

In other words, for a statically stable airplane, the pitching moment curves versus angle of attack or versus lift should have negative slopes at the point of equilibrium. Because the airplane rotates around its CG, the above considerations imply that for a stable aircraft the aerodynamic center[3] must lie aft of the CG.

When a lifting craft operates near the underlying surface, both its pitching moment and lift depend not only on the vehicle's angular orientation with respect to that surface (pitch angle), but also on its distance from the surface (ground clearance). In this case, the increment of lift induced by a perturbation may be caused by the resulting variation of both pitch and ground clearance.

Using quasi-steady aerodynamic derivatives, Kumar [88] derived equations of longitudinal and lateral motion of a WIG vehicle, linearized around the design angle of pitch and ground clearance. He reduced these equations in the frequency domain to a characteristic *quintic* equation for a general case of perturbed forward speed of the vehicle. He considered particular cases corresponding to a concept of stability under constraints, which implies that

[3]The center of application of the increment of lift.

controls are deliberately operated in such a way as to keep a chosen element of disturbance at a constant value. Kumar applied his analysis to predict stability of a monoplane wing with endplates and a tandem of two wings of equal aspect ratio and planform area,[4] both wings having the Clark-Y foil section. Both configurations were found to be unstable in GE. Kumar commented that one of the approaches to secure pitch stability of a WIG consists in appropriate design of foil sections.

In 1970 Irodov published his work [43] on longitudinal stability of ekranoplans. In a fashion applied in dynamics of airplanes, he assumed that perturbed motion takes place at constant speed, and reduced the corresponding characteristic equation to a *quartic*. Irodov formulated the criterion of longitudinal static stability as the requirement that *the center in height should be located upstream of the center in pitch*, Fig. 52.

Introducing abscissas of these centers correspondingly as

$$x^h = m_z^h \Big/ C_y^h, \quad \text{and} \quad x^\theta = m_z^\theta \Big/ C_y^\theta,$$

where h is the ground clearance related to the chord, θ is pitch angle in radians and the axis x is directed upstream, one can write Irodov's criterion

$$x^h - x^\theta > 0.$$

Having obtained a simple formula for re-calculation of the above centers from one reference point (position x_{cg} of the CG) to another, Irodov showed that displacement of the CG in the upstream direction entails shifting of the center in pitch towards the center in height, resulting in decrease of static stability margin. It also follows from Irodov's work that

> If the analysis referred to the trailing edge shows that the vehicle is stable, it should remain stable for any position of the center of gravity upstream of the trailing edge.

Staufenbiel and his colleagues considered somewhat more general approach, accounting for perturbation of forward speed [87,89–94]. As in [88], Kumar reduced the consideration of stability to the *quintic* characteristic equation. To evaluate longitudinal static stability Staufenbiel introduced the *static height stability parameter* which he defined as the derivative of lift coefficient C_y with respect to ground clearance for a fixed (zero) magnitude of longitudinal moment coefficient m_z.

[4]In the latter case the forward wing had endplates, so that the wing elements of the tandem were not identical.

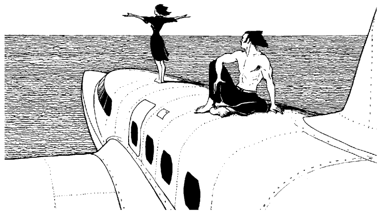

Fig. 52. For static stability of longitudinal motion, the center in height should be located upstream of the center in pitch.

His criterion of static stability is expressed as

$$\frac{dC_y}{dh} = \frac{\partial C_y}{\partial h} - \frac{\partial C_y}{\partial \theta} \cdot \frac{\partial m_z}{\partial h} \Big/ \frac{\partial m_z}{\partial \theta} < 0.$$

Essentially, the latter inequality shows that the stabilizing effect of $\partial C_y / \partial h$ should exceed the destabilizing influence of the nose-down moment. Note that Zhukov [95] also used the derivative of lift coefficient with respect to height (for zero magnitude of the moment coefficient) and the term *force stability criterion* and pointed out that this factor determines to a considerable extent the controllability of the vehicle and its response to the action of wind. Accounting for the fact that for a properly designed WIG effect vehicle $\partial C_y / \partial h$ should be negative, one can re-write the previous inequality alternatively as

$$1 - \frac{\partial C_y}{\partial \theta} \cdot \frac{\partial m_z}{\partial h} \Big/ \frac{\partial m_z}{\partial \theta} \cdot \frac{\partial C_y}{\partial h} = 1 - \frac{x^h}{x^\theta} > 0,$$

$$F_m = \frac{x^h}{x^\theta} < 1.$$

This equation constitutes another form of Staufenbiel's static stability criterion which is seen to be identical to that derived earlier by Irodov in [43]. Staufenbiel and Yeh [89] also analyzed the stability of the Lippisch craft X-113 and found that in all modes of flight with relative clearance under 0.5 the vehicle was dynamically stable. Recently, Taylor [96] has carried out an elegant experimental verification of the stability of a schematized *Lippisch* configuration.

Based on previous evidence, see Kumar [88], that a single wing with a conventional Clark-Y-type foil sections is unstable, Staufenbiel and Kleineidam [92] and Kleineidam [97] provided an interesting analysis of the longitudinal stability of a single wing geometry.

Stating that Clark-Y *"...can hardly be claimed as an airfoil very suitable to application in WIG vehicles due to lack of height stability..."*, the authors conducted an analysis of the effect of foil section geometry upon static stability and concluded that "unloading the rear part of the lower surface, which increases with ground proximity would be favorable for height stability".

It was shown that a simple way of augmenting stability of the Clark-Y foil consists in providing this foil with a trailing edge flap, deflected to an upward position, Fig. 53. Furthermore, the authors found that if unloading of the rear part of the foil is combined with de-cambering of the foil the stability range can be enhanced quite noticeably. It was found that the foil class providing the aforementioned synthesis should have an S-shaped mean line. It is worthwhile mentioning that S-shaping of the foil's mean line as the method of improving longitudinal stability of airplanes has been known for years.

Back in the 30s, a Russian engineer Cheranovsky built an experimental airplane with S-shaped foil sections. This airplane showed better stability though worse aerodynamic characteristics. In their stability prediction for an S-shaped foil, Staufenbiel and Kleineidam used an approximation of the foil's mean line with a cubic spline function the parameters of which were selected in such a way as to provide the maximum range of lift coefficient in which the foil was stable. The resulting static stability characteristics of the Clark-Y foil, the same foil with upward deflected flap and the aforementioned optimized foil are presented in Fig. 54.

Figs. 55 and 56 show the pressure distributions for a foil with straight lower side and a foil with optimal S-shaping.

Upon extension of their stability analysis to 3-D wings in ground proximity, the authors concluded that the way of shaping the airfoil for better height stability has the same effect for a rectangular wing with a modified airfoil section. Other practical results of [92] concern the influence of the geometry of wing tips upon longitudinal static stability, Fig. 57. Calculations showed that both use of endplates and sweeping of the wing's tip sections produces improved longitudinal static stability.

An experimental investigation of the influence of the form of the airfoil upon its static stability was carried out by Gadetski [98]. Based on results of his research the author indicated that it is possible to control the location of aerodynamic centers by means of proper design of the foil. He showed

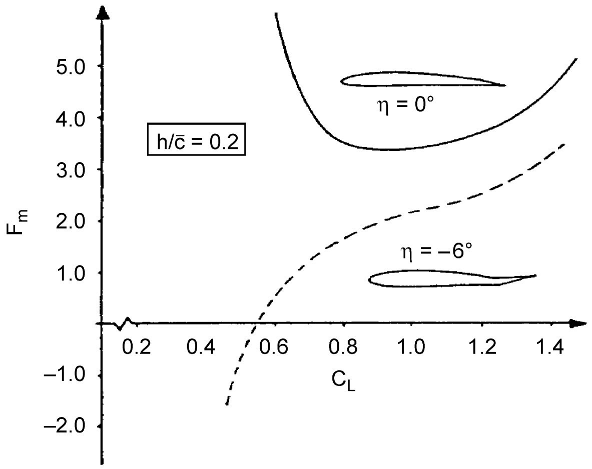

Fig. 53. Influence of the upward deflected flap on static stability (from Staufenbiel and Kleneidam).

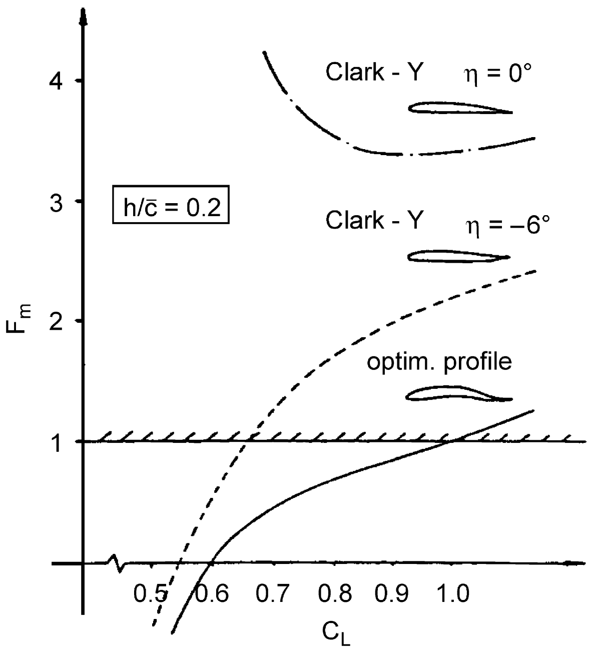

Fig. 54. Comparative static stability for three foils.

experimentally that an upward deflection of the rear part of the foil near the ground serves to move the center in height upstream and the center of pitch downstream. Arkhangelski and Konovalov [99] performed a similar investigation by the method of numerical conformal mapping and an experimental technique of fixed ground board. Treshkov and Plissov [100] studied the static stability of a lifting system comprising two wings of finite aspect ratio. Kornev [101] considered a class of foils with

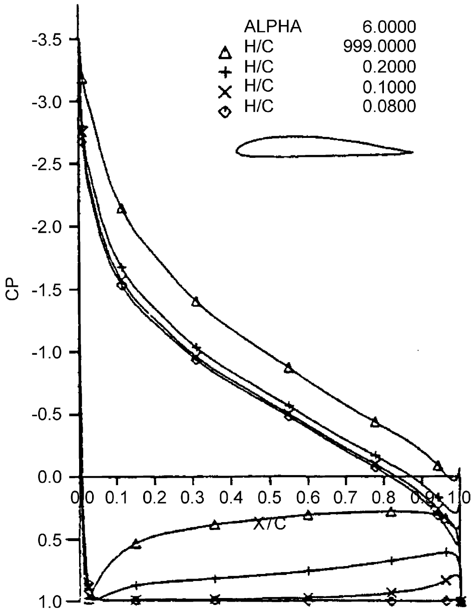

Fig. 55. Pressure distribution on Clark-Y foil with strait lower side.

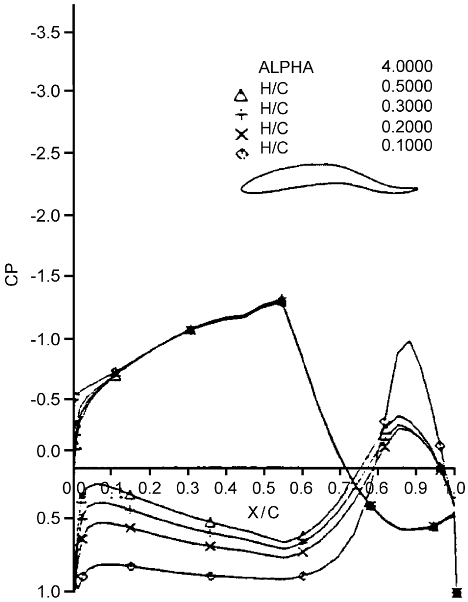

Fig. 56. Pressure distributions for a foil with optimal S-shaping.

S-shaped camber line using the discrete vortex method which was validated experimentally by Shin et al. [102]. Paper [102] also presented some numerical data on the influence of position and planform geometry of side wings upon static stability of a composite wing configuration, the main wing of rectangular planform being equipped with endplates.

Rozhdestvensky [103] applied *mathematics of EGE* to investigate the influence of the form of the cross-section of the wing and endplates in the case when a wing system advances in very close proximity to the underlying surface. This study employs the fact that close to the ground stability characteristics of the foil and finite wing are mostly determined by variation of the pressure distribution on the lower side.

Note that, Staufenbiel and Kleineidam also indicated:

> …the ground effect mainly influences the pressure distribution on the lower side of the foil. Therefore, the derivative of the c.p. position might be influenced by choosing a suitable shape of the lower surface…

It follows from both theoretical and test data relevant to the development of WIG effect vehicles, that at present there exist several optional types of aerodynamic configurations which can ensure static

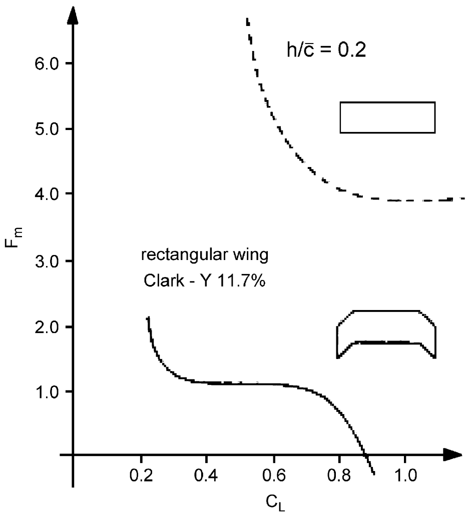

Fig. 57. Influence of the geometry of wing tips upon its stability in ground effect (a) wing with endplates, (b) wing with swept tips.

stability over a certain range of pitch angle and ground clearance.

Use of a large and highly mounted horizontal stabilizer, serving to shift the center in pitch rearwards and only slightly affecting the position of the center in height, enables one to ensure static stability over a wide range of pitch angle and ground clearance, including regimes of maximum lift-to-drag ratio.

The designers of the large Russian ekranoplans opted for placing the rear stabilizing surface behind the main wing and out of the influence of GE. Lippisch-type configurations also employ high-mounted tails for better stability which is further enhanced by the special design of the main wing which has a *reverse delta* planform with an inverted dihedral. However, Onspaugh [104] emphasized the negative side of the above option that a horizontal tail of sufficient size provides height stability but leads to a remarkable increase in structural weight. The ARPA "Wingship Investigation Final Report" [8] states that an increase of the size of a horizontal stabilizer over conventional aircraft for the same moment arm with conventional wing planforms will range between 20% and 80%, depending on wing aspect ratio and allowable fuselage pitch angles for takeoff and landing.

Another option is the use of a tandem wing configuration. When developing his 3 ton SM-1 prototype, Rostislav Alexeev borrowed a tandem configuration from his designs of hydrofoil ships [13]. Günter Jörg applied a tandem configuration in the design of his "Aerofoil-Flairboats" [105]. As referred to earlier, in a particular case of a tandem with wing elements, which were identical except for the endplates on the forward one, Kumar found that tandem configuration was unstable. However, both Alexeev's and Jörg's WIG effect craft developments represent "live" evidence that with an appropriate aerodynamic layout this configuration can achieve stable flight. The range of angles of pitch and ground clearance, for which a tandem configuration ensures stable flight, is somew hat restricted. In particular, as follows from testing experience for the SM-1 prototype, this scheme does not provide stability and safety when the vehicle flies farther from the ground, see Sokolov [106].

A suitable combination of airfoil sections, wing planform, endplates, side wings or winglets can lead to satisfactory height stability with tail of reduced size or even without a tail. For example, incorporation of S-shaped wing sections into design of ekranoplan MPE enabled to reduce the reference area of horizontal stabilizer to 27% of that of the main wing [13].

As future WIG effect craft are designed to fly at small relative distances from the ground, a reference to the paper [107] may be of interest which discusses the asymptotic form of the equation of longitudinal motion in EGE. It is shown that in close proximity to the ground the parameters of stability and motion of the lifting system depend on the ratios of design pitch angle and curvature of the lower side of the wing to the relative ground clearance h as well as on a "reduced" density of the vehicle $\bar{\mu} = \mu h$, where the density μ is defined as $\mu = 2M/\rho S C_0$.

It was also shown that at distances of the order of the chord from the moment of perturbation, the equations of motion correspond to the "quartic" formulation of Irodov, i.e. the speed of the vehicle remains almost constant. At larger distances of the order of $chord/h$ and $chord/h^2$ from the moment of perturbation one can observe a variation of speed which is first driven by height and pitch perturbations and later is determined by the speed perturbations proper. The latter conclusion confirms results, derived by Zhukov [108]. In fact, these results justify Irodov's criterion of longitudinal static stability based on the characteristic equations of the fourth order.

9. Takeoff of WIG effect vehicles

The large power required for takeoff is the most important impediment to the development of the technology. Usually the vehicle has to carry about 2–3 times more power than needed in cruise, as shown in Fig. 58.

One of the major issues in solving the problem of efficient takeoff and landing is maximization of the lift coefficient in alighting modes.

9.1. Lift coefficient at takeoff

The theory of EGE predicts the following upper bound of the lift coefficient for the case of a foil with flat lower and parabolic upper side:

$$\max\ C_y = 1 + \frac{2\theta}{\pi}\ln\frac{\pi}{\theta} + \frac{8\delta_t}{\pi},$$

where θ and δ_t are pitch angle (in radians) and relative thickness. Evidently in this equation the first term, equal to unity, represents the maximum contribution to the lift one can expect from the lower surface of the wing (w/o PAR). Calculations based on this equation show that the estimate made by Reeves of a maximum lift coefficient obtainable for a WIG effect as $C_{y\,\max} \approx 1.6$ is quite reasonable. Rozhdestvensky [1] derived an approximate formula for the ratio of the maximum lift coefficient with power augmentation

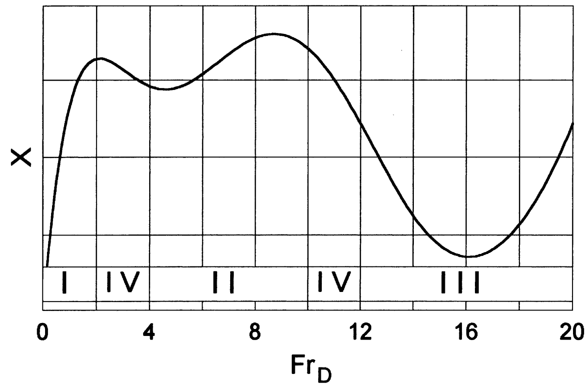

Fig. 58. Characteristic drag curve of ekranoplan of the first generation (I—floating, II—planing, III—flaring in ground effect, IV—intermediate regimes) [57].

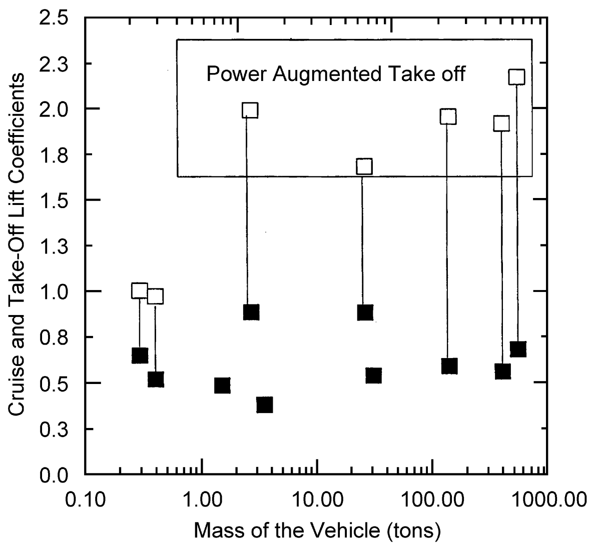

Fig. 59. Magnitudes of cruise (black squares) and takeoff (empty squares) lift coefficients for wing-in-ground effect vehicles.

to that without PAR:

$$\frac{C_{yto}^{\mathrm{PAR}}}{C_{yto}} \approx \frac{1}{1 - k_j^2 T_S / 2w},$$

where k_j is the coefficient of decay of the velocity in the system of turbulent jets during their evolution from the exit of PAR engines to the entrance cross-section of the channel under the wing. The parameter $T_S = T/S_j$ (where T is installed thrust, S_j is overall nozzle area of the PAR power plant) can be called *specific* installed thrust. The parameter $w = M/S$ represents the wing loading. One can conclude from this equation that PAR serves to decrease the speed of detachment from the water. It can also be seen that the takeoff efficiency of PAR depends on the reciprocal location of the wing and the PAR engines, the magnitude of specific installed thrust and the wing loading. Fig. 59 presents values of cruise and takeoff lift coefficients for existing and proposed WIG effect vehicles. It can be observed from the figure that in the case of power-augmented takeoff the values of the lift coefficients are larger than those without PAR-aided takeoff.

9.2. Liftoff devices and solutions

The large power required for takeoff is one of the most important impediments to the WIG effect technology, see [8]. A list of possible solutions may include

- Direct underside pressurization (DUP)

Applying pressure to the vehicle's underside results in a mode of operation during takeoff that is similar to a surface effect ship. In 1935 Kaario (Finland) applied DUP and built a ram-wing snow sled. In the 50s and 60s Bertelson developed dynamic air-cushion GE machines (GEMs). The DARPA report mentions a patent (T.W. Tanfield) for a "Near Surface Vehicle" which is essentially a small WIG initially using a diverted thrust air cushion to attain lift. At higher speeds the lift is provided by airfoils. A simplified "air cushion" takeoff aid was recently developed by Design Unlimited. It makes use of what the authors call a "streamlined low-pressure cavity". The tests conducted for different wing configurations (tandem, canard, reverse delta wing, rectangular, double delta) increased the acceleration rate by more than 80% and cut the takeoff distance in half.

As indicated by Fischer, the Lippisch craft X-113 was tested with an air-cushion landing device [109]. An inflatable rubber body, comparable to a hovercraft, was mounted around the fuselage of the X-113. This rubber body was kept by suction to the airframe to avoid additional aerodynamic drag during cruise. The oval shaped air cushion below the fuselage was filled with a separate blower of variable pressure in order to create a high-pressure air cushion as on a hovercraft. Towing tank tests showed significant reduction of drag, especially in the lower speed range. However, the imperfect hull shape increased the drag in waves. Thus, reduction of takeoff power was achieved only on calm water. On the other hand, the design enabled amphibious operation of the vehicle.

The DUP approach is used in the "Sever" air-cushion craft [110], Fig. 60. These high-speed amphibious boats use the following concept. Under a certain (critical) speed they are supported by a static air cushion. The skirt is designed in such a way that when the critical speed is exceeded the oncoming flow is let into the chamber so that at a normal cruising speed the vehicle is supported partly by the static air cushion and partly by the dynamic head due to forward speed. In other words, the skirt of the "Sever" craft has an ability to fold when the dynamic pressure head of the oncoming flow exceeds the static pressure in the air cushion, so that at high speeds the boat switches to the GE mode. The skirt has fore, aft and side components. The side skirt comprises inflated cylinders streamlined at both extremities. The fore and aft skirts, made of rubberized fabric, are attached, on one end, underneath the platform between the cylinders.

On the other end, the skirts are connected to the cables coming from the winch. The special features of these skirts are that

- they are collapsing and there is only a small drag penalty in negotiating obstacles,
- they are easily retractable in flight, significantly decreasing drag and allowing greater flexibility in selecting length/width platform dimensions.

The designers of "Sever" claim that this principle allows to configure an ekranoplan with any load lifting capacity. The use of collapsible flexible fore/aft skirts and pneumatic cylinders enables ekranoplans to takeoff from and land on any surface thus conferring enhanced amphibious capabilities.

It is worthwhile mentioning that at the end of the 80s Cheremukhin (Russia) had built a one-seat aircraft "Poisk" employing this type of air-cushion device for takeoff and landing [111] (Fig. 61).

Fischer used the idea of the diverted thrust air cushion in his *Hoverwing technology* [112], Fig. 62. It turned out that in transition between displacement mode and approximately 90% of the takeoff speed the air cushion is able to lift up to 80% of the vehicle's takeoff weight. At the same time, only 7% of the propeller disc area is diverted from the propeller main slipstream and guided through the air tunnel below the hull. When reaching the takeoff speed the dynamic pressure head replaces the static air cushion.

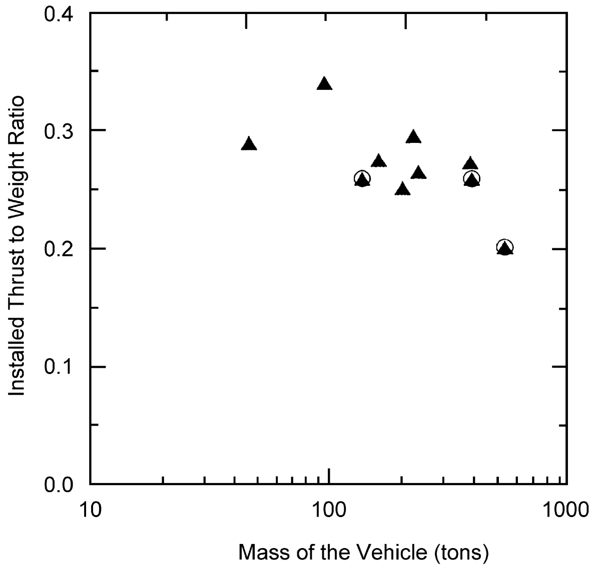

Fig. 60. Installed thrust-to-weight ratio of wing-in-ground effect vehicles (circles) and jet aircraft (triangles).

The sealing finger skirts are then automatically deflected to the underside of the hull. The inlet port behind the propeller is closed. The latter action produces two effects: (1) it deflates the bag-type skirt sealing at the end of the air cushion which is folded to the vehicle's lower side by the free air stream, (2) full thrust is made available for cruising. Thus, after reaching the takeoff speed, the craft operates in GE mode. Unconditional inherent longitudinal stability of the vehicle during transition to takeoff can be maintained by adjusting the rear sealing of the static air cushion and the forward sweep of the outer wings. Before landing the inlet port is opened again, the rear sealing inflates immediately after throttling up when reaching the water surface. Building up of the air cushion makes the front finger skirt sealing swing down automatically. As a result, the air cushion is working again after touchdown, which is reported to make the landing "extremely soft and reduces the structural loads".

Another way of pressurizing the vehicle's underside is connected with the blowing of the engine exhaust under the main wing and is known as power augmentation (PAR).

- Hydrodynamic drag reduction
  The primary hydrodynamic forces during the takeoff are hull drag, drag of the wing, its flaps and endplates. So, any method of hydrodynamic drag reduction can be employed to decrease the

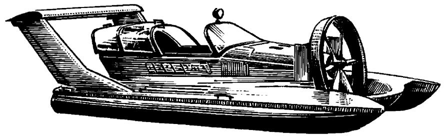

Fig. 61. The DUP vehicle “Sever”.

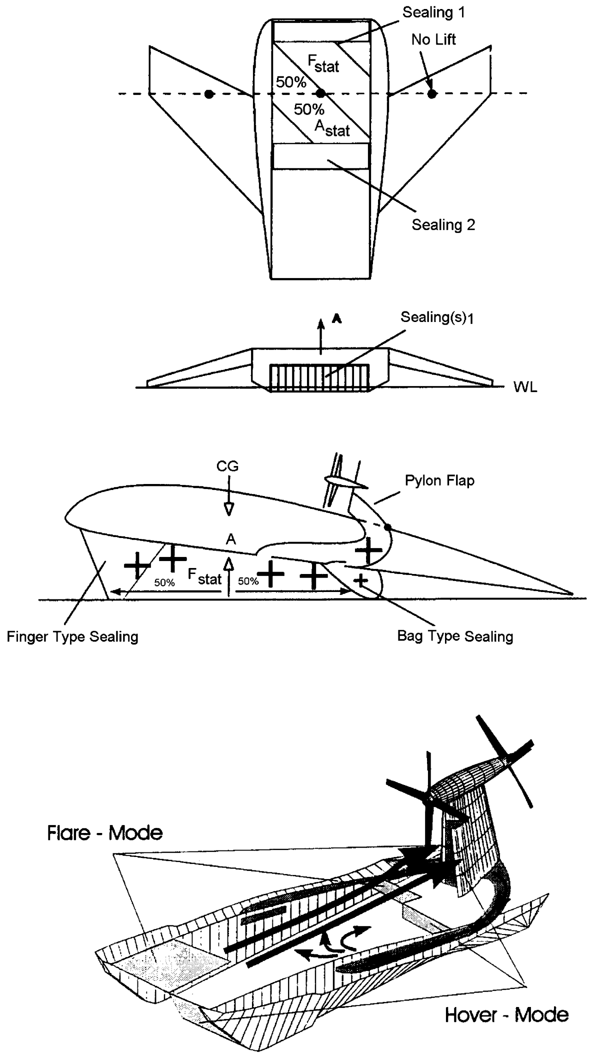

Fig. 62. Scheme of diverted thrust air cushion of “Hoverwing”.

power required to takeoff. Some potential might exist for the use of polymer solutions injected into the boundary layers of those surfaces of the wing-in GE vehicles which are in contact with water during the period of takeoff. Note that one of the major obstacles to implementation of the well known phenomenon (Toma effect) of viscous drag reduction through use of injection of polymer solutions on displacement ships are due to the necessity to store on board large quantities of polymer. For the WIG effect vehicle this difficulty is not insurmountable because during the takeoff the vehicle is in contact with water for only a few minutes.

- Aerodynamic high-lift devices
  In the DARPA Wingship report [8], various high lift methods are discussed, such as augmentation of camber, use of conventional and jet flaps, slots and different trailing edge devices. It should be noted, however, that not all devices beneficial for aircraft are as efficient on WIG effect vehicles. For example, in contrast to airplanes, trailing edge flaps do not create a considerable increase of lift in GE, the attainable lift coefficient being approximately near unity. These lift coefficients result in either high takeoff speed or huge wing areas. The effect of the flap may also result in a decrease of the longitudinal stability. The latter is regarded as absolutely essential for safe operation.
- Hydrodynamic high-lift devices (hydrofoils)
  Hydrofoils and hydroskis reduce the overall hydrodynamic drag by reducing the area in contact with water. According to DARPA ,the investigation shows that reasonably sized retractable foils can potentially lift a large wingship hull out of the water at speeds as low as 25–35 knots and reduce the hydrodynamic drag during takeoff for the 400 ton size vehicle [8]. Hydrofoils and hydroskis can be used to absorb landing loads, reducing peak loads on the hull structure, Fig. 63. On large Russian ekranoplans the hydroskis are employed in the vehicle’s landing phase. The challenges of this concept are cavitation problems, drag caused by suspension systems, overall structural integrity and weight penalties from hydroskis or/and hydrofoil-related mechanisms.
  Lippisch is known to have conducted full scale trials with use of retractable hydrofoils as takeoff aid. Two front mounted and one stern mounted hydrofoils were used on the X-114. Advantages were: reduction of the wetted surface, reduction of the outer float size of the catamaran configuration followed by a significant weight decrease of the vehicle as well as decrease of the tail size as the destabilizing influence of the floats diminished.
- Vehicle footprint (cushion area) variation [8]
  It may be possible to design a variable cushion area and variable length-to-beam ratios. This

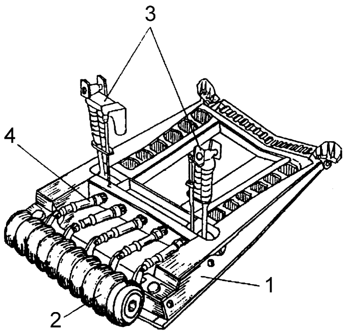

Fig. 63. Scheme of amortizing hydro-ski device of ekranoplan.

could result in significant drag reduction at high speeds. In fact, vehicles with low length-to-beam ratios have higher hump speed and a very high (wave) drag at this speed. On the other hand, craft with high length-to-beam ratios have a higher hump speed and low drag at speeds around the hump speeds. The concept is to operate at high length-to-beam ratios at low speeds and low length to beam ratios at high speeds.

- Leading and trailing edge (Fowler) flaps to increase wing area [8]
  This potential solution increases the wing area which for the constant lift coefficient would reduce the takeoff speed and, consequently, potentially reduce loads on the vehicle structure due to wave impacts, thus reducing the empty weight fraction. Another benefit of increasing the wing by the use of the forward and rear (Fowler) flaps is that it increases the length-to-beam ratio of the pressure patch entailing augmentation of the hump drag speed.
  The benefit of increasing the latter is that the peak drag forces at high hump velocities are less than the peak drag forces at lower hump velocities. A problem with this approach is that it does require additional vehicle complexity and may increase the weight.
- Peripheral jets in endplates floats [8]
  Peripheral jets in the wing's endplates may improve PAR efficiency by sealing the pressure under the wing and may augment the vehicle's thrust. Peripheral jets were used extensively on the hovercraft in the "early days" as means of providing the air cushion beneath the craft. The jet also provided the air curtain with a blowing angle optimized for cushion pressure and cushion area.
- Rechargeable stored energy burst thrust [8]
  Some ideas and concepts are known regarding momentary thrust augmentation during takeoff. One approach is to develop engines with thrust augmentation capability. Other approaches include using rockets to assist takeoff by providing a system where excess energy during one phase of operation is converted to stored energy for use during takeoff. There are some impediments to implementation of these ideas, e.g. the rocket concept reduces the vehicle's flexibility because it can only takeoff from sites where the rockets can be reloaded.

9.3. Power augmentation for takeoff and cruising

9.3.1. PAR

The specific technique of aiding takeoff and, perhaps, landing by directing the efflux of forward mounted propulsion units under the wing is called *air injection* in Russia and *power augmentation* (the abbreviation *PAR* stands for power augmented ram) in the Western countries, Figs. 64 and 65.

PAR has been shown to reduce the power for takeoff and the impacts of the oncoming waves in alighting modes. Suggestions to use blowing under the main wing date back to the Warner "compressor plane", Bartini and Alexeev. The latter two engineers managed to implement this technique, correspondingly, for the seaplane VVA-14 making use power augmented takeoff and landing and the large ekranoplans of the first generation (KM and its derivatives).

In 1962 Alexeev was the first to apply the underwing blowing to improve the takeoff and landing characteristics of the SM-2 model [12].

The blowing system, however, aggravated the pitch stability problem for the tandem configuration. Lippisch used PAR in 1963 on his X-112 craft and was able to increase the lift coefficient of the Clark-Y airfoil section by 25% as compared to that w/o PAR. Half of the propeller area blew air under the wings and could be controlled by smaller flaps behind the propeller. Fischer tested PAR on his Airfish AF-3 PA version by installing two tiltable propeller units of 20 hp each at the bow of the vehicle. Thereby the takeoff weight could be raised from 750–900 kg, and the takeoff distance, especially under waves, could be shortened significantly.

Another design concept is a vehicle that cruises on PAR (Volga-2, Amphistar-Aquaglide, Swan-I and II). As a result, the maximum takeoff drag-to-lift

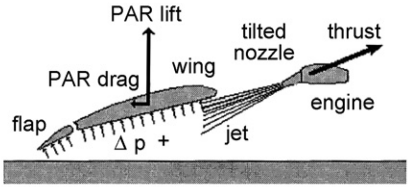

Fig. 64. Scheme of generation of lift force in PAR mode.

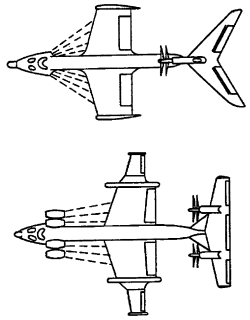

Fig. 65. Schemes of power augmentation for airplane and composite wing configurations.

ratio for the ekranoplans in smooth water of 0.17–0.2 was achieved, almost 2 times less than that for the conventional seaplanes. In PAR mode, used either for takeoff or as a permanent feature, a superposition of the dynamic air cushion due to forward speed and the power augmented air cushion occurs, accompanied by interaction of the propulsor-generated turbulent jets with the main lifting surface. The efficiency of PAR in reducing the takeoff speed depends on the reciprocal arrangement of the main wing and PAR engines, the wing loading and the ratio of the installed thrust to weight [3]. Based on the Russian data, the rough water drag for ekranoplan with PAR is 24% larger than that for the calm water. The rough water drag for a WIG effect vehicle w/o PAR is 42% larger than the calm water drag. A WIG craft with PAR has the lowest amount of drag for either case. Generation of power augmented lift is usually accompanied by decrease of the *thrust recovery fraction* (*TRF*), resulting in longer takeoff runways. The TRF shows how much of the PAR engine thrust can be recovered for acceleration of the vehicle. The rational combination of PAR efficiency (expressed as a weight to thrust ratio) and TRF can be identified with help of the so-called *PAR efficiency envelopes* introduced by Gallington et al. [84] on the basis of the potential flow theory and jet-momentum theorem. In this analysis a "re-entrant jet (RJ)" model of interaction of turbulent jets with the leading edge of the main wing was used. The RJ scheme implied separation of the PAR engines exhaust jets from the leading edge. To evaluate the increase of efficiency due to the tendency of the jet to envelop the rounded leading edge, a corresponding approximate "Coanda effect" model was proposed in [3].

During the takeoff large water sprays are formed which, under certain conditions, can spread all over the craft's structure including the bow section. As indicated by Kirillovikh [11], when the takeoff technique is not properly defined—a "pumping" of the engines and, consequently, their "shut-down" can occur due to a failure in the combustion chamber and/or water penetration into the engines" venting parts.

Optimal longitudinal position of the engine's nozzles with respect to the craft depends on the specific engines and on the specific design of the ekranoplan. Both theoretical solutions and experimental data suggest that a specific ratio of the jet area to the inlet area of the channel under the wing (at its entrance) is required for the optimal performance at each trailing edge gap setting. This optimum jet area is usually larger than the exit area of the conventional propulsors. Fortunately, entrainment causes the jet area to increase in the downstream direction. Therefore, for the propulsor whose area is less than optimal the maximum performance occurs with the engines well upstream of the wing. Gallington defined three possible cases [84]. The channel may be (1) *underfilled*, where a region of stagnated air forms near the surface; (2) *filled* where the exhaust completely fills the channel opening or (3) *overfilled* where some of the flow spills over the top of the main wing.

9.3.2. USB PARWIG concept

The USB PARWIG concept (Murao [113]) is a craft which employs the front wing with upper surface blowing and the rear WIG effect in a tandem arrangement. The comparison of the USB PAR with a tilted-propeller PAR in terms of lift shows (as stated by the authors) that remarkable gains can be obtained by the former, Fig. 66.

The WIG scheme with PDS PAR comprising a PDS (propeller deflected slipstream) fore wing and GE rear wing in a tandem configuration was proposed by Professor Murao [114]. This study compares wind-tunnel performance of PDS PAR with a conventional PAR-WIG with tilted propeller and finds a reduction of both required thrust and

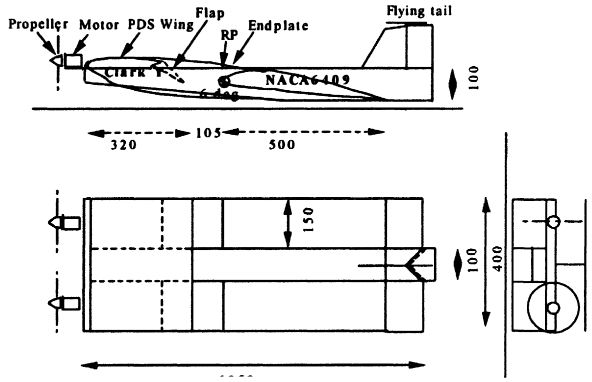

Fig. 66. Wind tunnel model of PDS PAR-WIG investigated by Murao.

speed by 30% in the former case. Radio-controlled models also showed that the takeoff length of the proposed WIG scheme was shorter than that of conventional seaplanes.

The authors state that the failure to reach the commercial market for WIG craft is associated with inefficient takeoff devices and poor seaworthiness. They underline that the PAR effect is remarkable, but the lift of the thruster proper does not contribute much. Hence the proposed concepts of USB PARWIG and PDS PAR-WIG. The latter is similar to the former and includes a fore-wing with full span flap and propeller system. To compare with PAR-WIG the rear wing and its incidence were taken similar in the case of PDS PAR-WIG. Through increase of the thrust they attained zero longitudinal force which corresponds to the self-propelling condition. This condition was reached at smaller thrust coefficients for the tilted propeller case, which due to the drag of the tilted propeller was smaller than that of the PDS.

The lift coefficient of the tilted propeller WIG was less than that of the PDS PAR-WIG. A 20° flap deflection was found appropriate. The authors found that the PDS PAR-WIG model has a tendency toward what they call "jumping takeoff".

10. Structural design, weights and materials

WIG effect vehicles present unique technology problems in structural design because they operate in air and water. Structures must be designed for both aerodynamic and hydrodynamic loads in highly corrosive conditions. In other words, the structure must be strong enough to hit the water, but light enough and configured to fly efficiently. These factors create stringent requirements for design. An example of design dilemma for a wingship structure is that large size and load factor would suggest use of lighter composite materials, but some composite materials are poor energy absorbers and would not tolerate the water slamming loads absorbed by a vehicle.

Structural issues become more difficult as the structure increases in size. For example, using given materials and structural design one cannot just simply go on making conventional airplanes larger and heavier. For a given material, concept and technology, the empty weight fraction[5] would grow, leaving an unacceptably low payload fraction.

One may speak of *a curse of the square-cube law*. The latter reads: *The stress in similar structures increases as the linear dimensions if the imposed load is proportional to the structual weight, since the latter grows as the cube of linear dimension and the material cross-section carrying the load grows only as the square*.

Some experts assume that going for larger and larger vehicles *the curse of the square-cube law* can be overcome through use of new (e.g. all wing) aerodynamic configurations as well as by changing the structural concept and materials.

Hooker's studies indicated an empty weight as low as 20% for a 500 ton ekranoplan. He states that Russia built ekranoplans with very large empty weight fractions ranging between 60 and 75%, but they were intended to sea-sit, were built at that time by ship designers and builders, and were the first ever built. Hooker predicts for his 5000 ton wingship empty weight fractions of 35% and 40%. He claims that using all carbon, structural weights approaching 12% are possible for the wingship. As a point of reference the supersonic B-58 bomber (designed to high dynamic loadings) was a stainless steel airplane employing braised honeycomb panels and had a 14% structural weight fraction.

The design of a wingship structure requires merging of two technologies: aircraft design and high-speed ship design. Both technologies have one criterion in common: that is to design a very weight efficient structure with high resilience and good producibility. High loads of the takeoff and landing conditions require substantial *scantlings*. This

[5]Hooker defines empty weight as the ratio of the operational empty weight (OEW includes engines and all controls and equipment necessary for standard operation) to the takeoff weight.

makes it feasible to use welded joining methods due to the plate thicknesses required for the fuselage and wing skin plating, thus maintaining the required *buckling strength*. This approach reduces the weight penalties for lower strength aluminum alloys. About 60% of the Orlyonok structure and about 90% of the Loon structure were welded. Another reason for using welded joining methods was the difficulty of maintaining water tightness of riveted or bolted connections in the waterborne conditions. In addition, the fabricating costs are substantially reduced.

The gliders of large Russian ekranoplans were made of appropriate aluminum alloys which had to comply with the following requirements

- high strength combined with sufficient viscosity of destruction,
- high magnitude of specific strength,
- capacity to withstand variable loads,
- high corrosion resistance,
- weldability.

Needless to underline that the last two properties are of utmost importance in shipbuilding. For example, the glider of the search-and-rescue ekranoplan was manufactured from alloys AMg 61 (1561) and K48. The riveted fuselage of one of Orlyonok's prototypes was made of a special aluminum alloy K48-2T1, see Kravchuk et al. [115]. This alloy based on the aluminum–zinc–magnesium and cuprum system had been developed by shipbuilding enterprises. Later on AMg-61 weldable alloy was used for "Orlyonok" (which applies to the basic fuselage, the wings, the endplates and the hydroski) and K48-2T1 was only used for internal riveted structures, such as decks, transverse bulkheads and partitions. Stainless steel is used for the engine pylons which require high strength and heat resistance. Whilst the main hull material for larger ekranoplans will probably remain limited to highly tensile steel and aluminum alloys, many other major components of these craft may well benefit from the use of fiber-reinforced plastics. The advantages of using composite materials in the fast ships industry have been recognized, see Fridlander (1992) and Ho (1995):

- low weight (results in increased speed, increased payload and reduces fuel consumption),
- fire resistance,
- high stiffness (reduces or eliminates supporting framework),
- durability (excellent fatigue, impact and environmental resistance, fiber-reinforced plastics are non-corrosive),
- rapid fitting,
- improved appearance.

The smaller craft may be manufactured entirely from composites. For example, a derivative of the Lippisch Aerofoil Boat "Airfish" is molded in two halves in plastic reinforced with carbon fiber, see Fischer [116]. The PAR vehicle "Aquaglide" (D. Synitsin) was manufactured with extensive use of fiber-reinforced plastics in the ratio: 40–45% glue matrix and 55–60% fiberglass fabric. The hull of the Aquaglide consists of the two halves: starboard and port, both of them manufactured as entire parts. The external skin-plating of the bottom, sides, awning and the hatch covers of the bow part of the craft were manufactured from a three layer composite material employing the glass-fiber. The filling of the hull is made with a foam plastic [12]. The force elements of the hull (in particular, the 3rd and the 4th frame spacing, the foundation for the main engine, the longitudinal girders of the bottom) are manufactured from aluminum magnesium alloy. The joining of the metallic details is made by welding, riveting and threaded joints.

The main structures of the ekranoplan are manufactured of corrosion-resistant materials and alloys: glass-fiber plastic, foam plastic, foam polyurethane, aluminum-magnesium alloys, stainless steel. When joining the chemically active pairs of metals, these are isolated from one another by means of glue and constructive clearances. Composite sandwich structures, as used on high-performance racing boats and on light aircraft can be tailored to local loads and can be manufactured at low cost. Using a combination of carbon fiber and glass fiber with thermoplastic matrix can result in a structural weight savings of 15–25% compared to aircraft aluminum.

11. Control systems [12,117]

The goal of the control system is to:

- transfer the control signals from the crew to the control organs,
- transfer the control signals from executive mechanisms of the automatic control system to the control organs,

- provide the necessary power for the deflection of the control organs,
- ensure and improve stability of the motion of the ekranoplan,
- provide the required steering characteristics of the ekranoplan,
- generate control signals for an automatic trajectory control of the ekranoplan,
- generate signals for the directional gauges for the regimes of semiautomatic piloting of the ekranoplan,
- enhance safety of motion of the ekranoplan by means of signaling and restricting the deflections of the control organs when approaching the limiting acceptable magnitudes of the motion parameters.

The main control systems for the ekranoplans are those of control of: height rudder, course rudder, flaps and tilting nozzles. Quite an effort is needed to activate some of the control elements of the ekranoplan. For example, a actuator of the flap of the Orlyonok generates a maximum effort up to 15 ton with a speed of the outer link of 200 mm/s. This means that such a drive requires a power of the order of 40 hp. For a Loon the hydro amplifier provides a maximum effort of approximately 20 ton with a maximum speed of the output link reaching 160 mm/s. The latter parameters correspond to about 42 hp. This is relatively large compared to hydraulic actuators used on large aircraft today. However, there are comparable or larger activators in terms of horsepower developed for the space shuttle launch vehicle.

A system of automatic controls is intended for

- damping of the angular oscillations of the ekranoplan in pitch, heel and yaw, as well as damping of a linear motion in height when applying the manual control,
- automatic stabilization of the magnitudes of pitch, heel, course and ground clearance established by the crew,
- correction by the crew of the established magnitudes of pitch and course,
- display on the piloting gauges indicators of the current magnitudes of pitch, heel, course and ground clearance,
- signals warning the crew that the ekranoplan has reached the limiting acceptable magnitudes of pitch, heel and flight height,
- automatic self-control of the ability to work, indication and localization of the failures,
- output of the signals, proportional to the pitch, yaws and flight height.

The damping of the angular oscillations of the ekranoplan in pitch, heel and course as well as displacements in height is provided by a system of gauges of their angular velocities, amplifying stations and rudder aggregates, which act upon the rudder surfaces-height rudder, course rudder and flaps (in a flap and aileron regime). The generation of the control signals, proportional to a vertical velocity, is effected on the basis of signals coming from the accelerometers and height meters.

Low flight altitude and the short time period available to solve flight safety problems in case of different control system failures require some specific operational safety regulations to be complied with.

The probability of accidents with ekranoplans is much less than with aircraft, since the former has an "aerodrome" beneath the wings. Thus, an ekranoplan is almost always able to make an emergency landing in case of serious control system failure. However, the landing of the ekranoplan results in considerable loss in economy because the landing is being followed by the takeoff which requires maximum fuel costs under operating conditions of the ekranoplan power plant during the limit thrust modes.

These circumstances dictate the main regulations for the ekranoplan's control systems: maximum operational safety and provision of the crew with precise information about those failures which require an emergency landing.

The automatic control systems of ekranoplans (stabilization and damping systems) not only have to provide a steady lift, as for an aircraft (and even to a higher extent) but also have to ensure safe takeoff and landing modes.

Taking into account the specific nature of the flight in a strictly limited altitude range, the aerodynamic configuration of the ekranoplan is designed to facilitate and to minimize control actions of the crew during all flight modes and to reduce pilot errors. In the case of Aquaglide a special airscrew and flap deflection control system has been developed to help the craft accelerate to cruising speed. Basically, proportional airscrew and flap deflection is performed in the takeoff mode, so that trim angle remains unchanged, i.e. with no change of the longitudinal moment. This is achieved by the simultaneous movement of the control levers in the cockpit. It is obvious that a decrease of airscrew and flap incidence angles reduces the lift. Accordingly, it would be assumed that the craft loses altitude with this change. However, if the change is carried out during vehicle acceleration, the loss of lift is compensated. In this case no reduction in altitude can be expected. However, this happens to be totally dependent on how fast the change is performed.

It is clear that the ram-wing concept is especially susceptible to active control, because small changes of the flow in the vicinity of the trailing edge may bring about a considerable change of the lifting capacity.

Real-time information is needed on the current motion coordinates in order to provide effective operation of the AMCS of the ekranoplan: angles of heel and pitch, angular velocities, ground clearance, speed of flight, vertical velocity, loads, etc. Hence there is a need for *measuring of the motion coordinates.*

Flight in GE poses particular requirements for the measurement of the coordinates. For airplane control the angles of pitch and heel are weakly controlled intermediate coordinates. Their real-time measurement is employed only for maneuvering in height and heading control. Errors in the measurement of heel and pitch of the order of units of degrees is considered as quite acceptable. The ekranoplan can move only in a very restricted combination of ground clearance, angles of pitch and heel. Outside this combination there exists a danger of contact of the extreme points of the structure with the underlying surface. Therefore, for the ekranoplan, in contrast to airplanes, the angles of heel and pitch play an independent role, and should be measured with errors not exceeding 15–20 angular minutes in all regimes of motion, including acceleration, braking and turning, i.e. in the high-load conditions.

The application of height meters is excluded because of their low accuracy. Acceptable accuracy of the order of 0.1–0.2 m is ensured by measuring devices which employ a contact (by means of radiation) with the underlying surface. These may be, in particular, radio height meters for small ground clearances, as well as isotopic and optical height meters.

However, when using the aforementioned height meters there appear certain specific difficulties. For example, when these devices are used over a perturbed sea surface, there appears a wave component in the output signal. This component varies with the frequency of the encounter of the craft with the wave and has an amplitude equal to that of the wave. A control system which makes use of such a signal, tends to make the ekranoplan follow the variation of the sea surface, i.e. to envelop the wave. This phenomenon would at best induce high-frequency fluctuations of the rods of the automatic rudder mechanisms, and, consequently, the wearing of these mechanisms and increased expenditure of energy. In the worst case, there may take place a perturbation of the motion of the ekranoplan proper, which can cause resonant oscillations of the craft in the vertical plane. As seen from this example, the signal variations due to sea waves should be considered as a hindrance which has to be alleviated.

In order to optimize the process of motion control of the ekranoplan, it was necessary to ensure continuous (along the whole route) measuring of the wave height under the wing, because the selection of the regime of flight of the vehicle depends on the roughness of the sea.

Another important question concerns the display of the flight information on the control panel. This information should be prioritized mostly on the basis of ensuring flight safety. The ekranoplan pilot should focus on the gauges displaying the ground clearance, angles of heel and pitch. When flying at small heights, it is very important for the pilot to know the current position of the vehicle with respect to the underlying water surface. That is why the piloted ekranoplans had a rear-view mirror. The KM had a special combined indicator, a pitch indicator on the left side and a heel indicator on the right side. In the bottom part of the gauge there was the height indicator in the form of a horizontal strip which moved up and down. Such a device allows the pilot to check the gaps, i.e. current distances of the lowest points of the ekranoplan from the underlying surface.

In order to control the height of flight of the ekranoplan one can use:

- deflection of the flaps,
- variation (trimming) of the pitch angle (with use of the height rudder),
- variation of the speed of flight (by varying the thrust),
- deflection of the flaps with simultaneous variation of the thrust.

As indicated, one can vary the height of flight of the ekranoplan without use of the flaps, just by means of variation of the air speed, because the lift, defining the craft's vertical motion, is proportional to the dynamic head of the air flow.

It is interesting to compare the effect of the speed variation in GE and out of GE. In the latter case this effect induces the motion of the craft with constant vertical speed. Near the ground the speed variation leads to a change in height, corresponding to a new speed. To change the ekranoplan's heading, similar to the turning of the airplane, one has to generate a side force. The latter arises due to the heel angle, yaw angle or due to a simultaneous development of the angle of heel and yaw (corresponding to regular, planar and combined turning).

It is known that the airplane can enter a regular power turn with angle of heel up to 50–60 deg without change of the flight height. For the ekranoplan the angles of heel and yaw, upon which depend the maneuvering characteristics, are considerably restricted to reduce the probability of contact of the structure with the water surface and to reduce the danger of such contacts. Even from purely geometric considerations, when flying at small height, it is necessary that the distance of the lower tip of the endplate of the wing from the water surface should not decrease in turning. To provide this the craft has to, first of all, perform the elevation of the ekranoplan in height—the so-called jump-up or fly-up.

To perform the jump-up one has to activate the channel of height, that is to also control the thrust. The increment of thrust is needed not only for passing of the vehicle to the new ground clearance but also to exclude a loss of height in the long-period motion due to the growth of the drag. The latter is connected with development of heel and yaw, as well as with inclinations of the course rudder, ailerons and flaps. Thus, the turning of the ekranoplan is a complicated three-dimensional maneuver requiring for its execution the activation of the channels of course, height, heel and speed control. Use of the combined means of turning with heel and yaw is stipulated by striving to enhance the efficiency of the turning with restrictions on the maximum values of heel and yaw, which are equally dangerous because of a possible contact of the structure with the underlying surface. When entering the combined turning maneuver, the value of the required thrust increases considerably. The effective combined turning should be applied in need of a considerable change of the heading of the vehicle. If the vehicle has to be turned several degrees, there is no need to make a complex three-dimensional maneuver with a jump-up. It is easier to execute planar turning.

Normally, when wishing to control the ship manually, the pilots should switch off the automatic stabilization. Such an approach is used mostly during the straightforward motion of the vehicle. In the process of executing maneuvers there often occurs an expediency and, in some cases, a necessity of simultaneous use of the manual and automatic control (combined control). The expediency of the combined control arises in emergency situations. In case of a sudden danger of collision with an obstacle in the path of the vehicle the pilot should have a possibility, without losing time on switching off the stabilization, to actively interfere in the process of steering.

One of the directions of ensuring flight safety of the ekranoplan when steering it manually is the development of a special "anti-accident" automatic device which should switch on when reaching dangerous values and return the ship to the domain of safe flight regimes.

12. Economics

One of the most important goals in the development of a transport system is its economic efficiency. One of the measures of the economic efficiency of a transport vehicle is the well-known Karman–Gabrielli diagram. Akagi represented this diagram in a reversed transport efficiency format [118]. Rozhdestvensky supplemented Akagi's data on several types of displacement and high-speed ships, airplanes, railway transport and trucks by corresponding data on Russian and non-Russian ekranoplans [1]. This reverse transport efficiency diagram showed that even existing ekranoplans, which are still far from optimum, have acceptable magnitudes of transport efficiency in their own speed range.

Today, the time of delivery of passengers and cargo becomes an extremely important factor when assessing the economic viability of means of transportation. The JIT (Just In Time) mentality is an urgent need in the present situation. The demand for speed (the modern travelers" tendency) which is an obvious advantage of the ekranoplan, as compared to other means of water transport, is well explained by the Bouladon chart, Fig. 67, where design speed is plotted versus design range for ekranoplans, air-cushion vehicles, hydrofoils and jet planes.

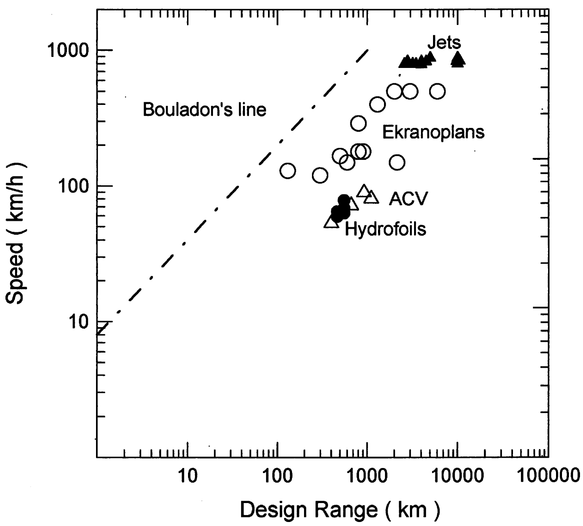

Fig. 67. Bouladon-type chart, characterizing demand for speed.

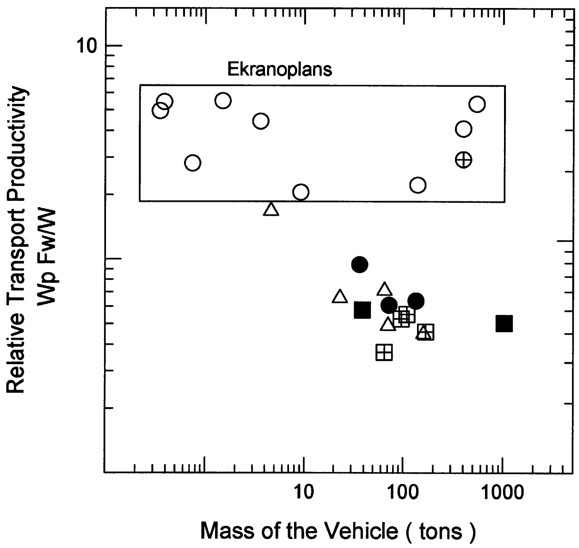

Fig. 69. Relative transport productivity versus mass for ekranoplans and other high-speed marine vehicles.

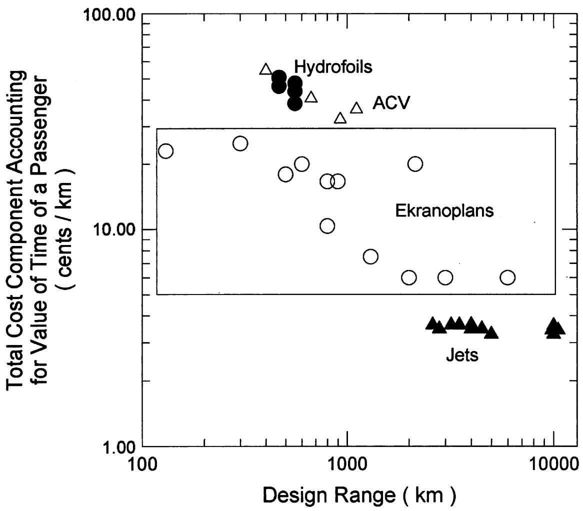

Fig. 68. Total cost component, accounting for the time of the passenger, versus design range of different vehicles, including ekranoplans.

The value of a traveler's time has become an important factor in present models of estimation of the economics of transport systems. Fig. 68 shows the total cost component accounting for the time of a passenger versus the design range of different vehicles, including ekranoplans. One can see that with respect to this parameter the ekranoplans fill in the gap between other fast ships and jet airplanes. The data for this figure have been calculated in a manner similar to that of Akagi and with use of additional information on WIG effect vehicles.

It is evident that the efficiency of a vehicle carrying some payload increases with speed. The faster the passengers (cargo) are delivered to a certain destination the better. That is why another useful measure of the economic efficiency is the so-called *transport productivity* which can be defined as the payload times the speed. Fig. 69 presents relative transport productivity versus the mass of the vehicle. The vertical axis represents the payload times the Froude number, based on a characteristic length equal to the cubic root of the volumetric displacement of the vehicle. On this chart ekranoplans look more attractive than other high-speed marine vehicles.

13. Certification of WIG effect vehicles [119–122]

13.1. Ship or airplane?

One of the crucial issues relevant to the use of a vehicle is its certification. Conceived to operate at the interface of water and air, a stumbling block is the argument between shipbuilding and aviation agencies as to the nature of the ekranoplan (WIG, WISES, Flarecraft, etc.). Is it a ship, navigating at aviation speeds, or an airplane choosing to fly near the sea surface to take advantage of the GE? The famous German engineer Hanno Fischer describes the distinction between a ship and an airplane from certification point of view in a simple albeit constructive comment: *"A ship should not be allowed to jump over the bridge, whereas the airplane is not supposed to fly under the bridge"*, Fig. 70.

There are several reasonable arguments to support the concept of the ekranoplan being a ship, in particular:

- the main operating mode is performed in immediate vicinity of water surface,
- takeoff and touchdown take place from (upon) the water surface,
- ekranoplans can float as conventional displacement ships,
- the ability of ekranoplans to temporarily increase altitude of flight in order to clear obstacles can be qualified as a short-time emergency regime.

As far as the last assertion is concerned, it should be kept in mind that the real height of such a "dynamic jump" is normally much less than the lower limit of altitudes prescribed for normal aircraft operations by the requirements of the ICAO.

Since 1991, many efforts were made to eventually make WIG effect vehicles a legitimate type of transportation. Although progress was quite slow, some practical solutions emerged in the absence of formal international regulatory recognition.

As reported by Jane's All World's Surface Skimmers (1994) in accordance with the Aircraft International Standards "...no special FAA certificate is required for operation of [Jörg's] Flairboats in any country". In connection with the Airfish, a derivative of Dr. Alexander Lippisch's Aerofoil Boats, the same source stated that "... the vehicle like a hovercraft, can be considered as a boat thereby avoiding the necessity of applying aircraft regulations and having a licensed pilot for its operation".

The same considerations appeared to be applicable to small vehicles with a permanent power augmentation feature (Volga-2, Amphistar, etc.), which have a high degree of aerodynamic "binding" to the ground and can be steered by ship operators without special pilot training. The WISES Marine Slider μ-Sky 2 was reported to have obtained a Ship Inspection Certificate from the Japanese Government.

In spite of these individual solutions of the problem under discussion, there emerged an urgent need for the establishment of internationally recognized regulations concerning WIG effect vehicles.

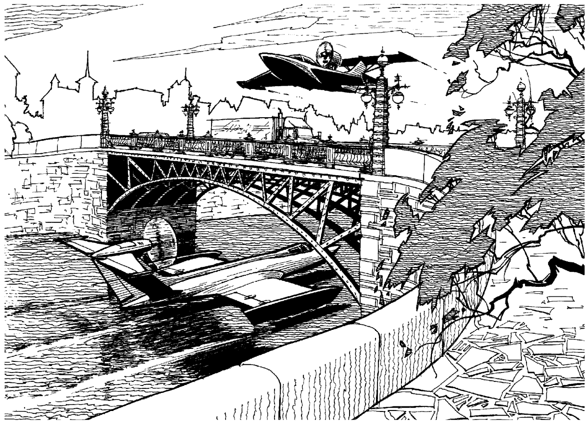

Fig. 70. Ship or airplane?

The traditional Russian approach has been to design wingships as ships that fly and not as aircraft that land on water. This approach avoids the complexities of design and safety requirements associated with aircraft certification. With this philosophy, a 280 knot wingship can indeed be considered the fastest type of marine craft afloat. The combat ekranoplans were designed according to the "design rules for combat surface ships" for the modes preceding the takeoff. In flight mode the "General specifications" for the development of combat aircraft were taken into consideration. The first large ekranoplans were impressive but were subject to no regulation rules due to the fact that they were developed and built for the purpose of National Defense.

13.2. Some hydrofoil experience

Let us recall the situation with hydrofoil craft in Russia. After having gained extensive experience in the operation of the "Raketa" first hydrofoil motor vessel, the designer, i.e. the CHDB, was ordered by the Register of Shipping to develop a draft of a supplement to the River Register Rules with reference to hydrofoil craft. When the craft was ready, the Register considered it and issued a provisional supplement to the River Register Rules with reference to the hydrofoil craft with some changes and additions. Similar craft were designed, built and operated using these provisional rules.

Using this experience, the Register later developed the final rules.

13.3. Progress in the development of regulations for WIG effect vehicles

Perestroika and conversion started in Russia in 1985 and promoted the introduction of ekranoplans as an alternative high-speed means of transportation. Subsequently, it became clear that commercial operation of these vehicles moving with aircraft speeds at sea level is impossible without national or international rules that would guarantee safety of their operation and establish a procedure for their inspection. The issue of the Rules was raised for the first time in 1991 by the leading experts of the CHDB, named after R.E. Alexeev. But at that time this appeal did not have adequate response in the industry and the regulatory agencies. In 1992 the Central Scientific Research Institute of the Ministry of Maritime Fleet (CSRIMMF) carried out the first attempt to certify commercial ekranoplans under contract with CHDB.

The main achievement of this document was that it had established the possibility to classify the ekranoplan as a vessel on a dynamic air cushion rather than as an aircraft. In particular, it was indicated that the ekranoplan operates in the environment of marine vehicles. It was shown that the Russian "rules of provision of safety for dynamically supported craft (DSC)" could, in principle, be extended to the case of ekranoplans, albeit with corresponding corrections and amendments accounting for the particular features of WIG effect vehicles.

Based on a thorough analysis of the situation, the document stated the necessity and urgency of including a section on ekranoplans into the IMO's Code of Safety for DSC Code. The corresponding proposals on ekranoplans were included in the document SLF 37/15/2, submitted by the Russian Federation to the 37th Session (held on January 11–15, 1993) of the Sub-Committee on stability, loading lines and safety of fishing vessels (SLF Sub-Committee) under the heading "Revision of the DSC Code" regarding stability. However, the SLF Sub-Committee quite justly decided that the principal question of affiliation of ekranoplans with other marine transports should be passed over to the Sub-Committee on Design and Equipment (DE) which was responsible for revision of the DSC Code and development of a new High-Speed-Craft Code (HSC Code) and recommended the Russian delegation to submit the proposal to its 36th session. At this session (held on February 22–26, 1993) the DE Sub-Committee

- stated significant level of activity and positive perspectives for the development of ekranoplans,
- agreed that ekranoplans should be considered as marine vehicles whose operational issues lie within the competence of the IMO,
- decided to include questions of safety requirements for ekranoplans in the IMO agenda and their subsequent inclusion in the new HSC Code or preparation of a separate IMO document,
- recommended to the Sub-Committee on safety of navigation (NAV Sub-Committee) to consider navigational aspects for ekranoplans,
- suggested to establish a joint IMO/ICAO working group with the goal to consider legal and navigational aspects of ekranoplans,
- formed a correspondence group for the development of the requirements on safety of ekranoplans, entrusting the Russian Federation with coordination of this work (Note that in 1998 the Ministry of Transport of the Russian Federation proposed the Russian Maritime Register of Shipping to lead the correspondence group).

These decisions were adopted at the 62nd Session of the Maritime Safety Committee (MSC 62/ WP.10). Thus, in 1993 the IMO made a historic step, having recognized ekranoplans as marine vehicles. With participation of CSRIMMF, JSC "Technologies & Transport" and foreign members of the correspondence group (representing ICAO, Germany, Australia, Canada, France, Korea, China Japan, UK, Hong-Kong and other countries) the Russian Maritime Register of Shipping prepared a draft of the International Code for Safety of Ekranoplans developed on the basis of the International HSC Code and applicable civil aviation (ICAO) requirements and submitted this document to the 42nd Session of DE Sub-Committee. The work initiated at the 36th Session of the DE Sub-Committee in 1993 was completed at its 45th Session in 2002 with acceptance of the "Interim Guidelines for Wing-In-Ground (WIG) Craft". The agenda item initially titled "development of the requirements for ekranoplans", but later the term "ekranoplan" was replaced by "WIG craft".

13.4. Main features of the "Interim Guidelines for Wing-In-Ground (WIG) Craft"

In these Guidelines a WIG craft is defined as a specific high-speed marine vehicle rather than as an aircraft. The ICAO definition of aircraft is "any machine that can derive support in the atmosphere from the reactions of the air, other than reactions of the air against the earth's surface". The WIG Craft is distinguished by employing (in the main mode of operation) the interaction with the air reflected from the earth's surface. According to the concept conceived by the Russian Federation, adopted by IMO and coordinated by ICAO, the WIG Craft is a vessel which is capable of flying (in contrast to the aircraft as a flying machine capable of floating).

According to the Interim Guidelines:

- A**"WIG craft"** is a multi-modal craft which, in the main operational mode, flies by using the GE above the water or some other surface, without constant contact with such a surface and supported in the air, mainly, by an aerodynamic lift generated on a wing (wings), hull, or their parts, which are intended to utilize the GE action.
- **"Ground effect"** is the phenomenon of increase of a lift force and reduction of induced drag of a wing approaching a surface. The extent of this phenomenon depends on the design of the craft but generally occurs at an altitude less than the mean chord length of the wing.

Very important for the goal of distinction (sharing) of competence between IMO and ICAO are provisions of the Guidelines categorizing WIG craft according to the following types:

1. **type A:** a craft which is certified for operation in GE;
2. **type B:** a craft which is certified to temporarily increase its altitude to a limited height outside the influence of GE but not exceeding 150 m above the surface; and
3. **type C:** a craft which is certified for operation outside of GE and exceeding 150 m above the surface.

The Guidelines specify the following **WIG craft operational modes**:

- "Amphibian mode" is the special short-term mode of an amphibian WIG craft when it is mainly supported by a static air cushion and moves slowly above a surface other than water;
- "Displacement mode" means the regime, whether at rest or in motion, where the weight of the craft is fully or predominantly supported by hydrostatic forces
- "Transitional mode" denotes the transient mode from the displacement mode to the step-taxi mode and vice-versa;
- "Planing mode" denotes the mode of steady-state operation of a craft on a water surface by which the craft's weight is supported mainly by hydrodynamic forces;
- "Takeoff/landing mode" denotes the transient mode from the planing mode to the GE mode and vice versa;
- "Ground effect mode" is the main steady-state operational mode of flying the WIG craft in GE;
- "Fly-over mode" denotes increase of the flying altitude for WIG craft of types B and C within a limited period, which exceeds the vertical extent of the GE but does not exceed the minimal safe altitude for an aircraft prescribed by ICAO provisions; and
- "Aircraft mode" denotes the flight of a WIG craft of type C above the minimal safe altitude for an aircraft prescribed by ICAO regulations.

The Guidelines emphasize significant differences between WIG craft and high-speed craft, in particular:

- substantially higher speeds of WIG craft and consequently larger distances traveled in a given time at operational speed;
- possibility of "amphibious" WIG craft being operated from land base;
- need for risk and safety levels to be assessed on a holistic basis, recognizing that high levels of operator training, comprehensive and thoroughly implemented procedures, high levels of automation and sophisticated software can all make significant contributions to risk reduction;
- reduced ability of WIG craft to carry and deploy equipment and systems traditionally associated with seagoing craft;
- changed use of traditional ship terminology, such as stability, for the safety of WIG craft in the operational mode and corresponding increase in the use of aviation terminology, such as controllability; and

- capacity of a WIG craft to mitigate hazards associated with its airborne mode by its ability to land on water at any time.

13.5. NAV Sub-Committee amendments to the COLREGs-72

A number of relevant proposals were made by the delegation of the Russian Federation to the NAV Sub-Committee. The work of this Sub-Committee under the agenda item "Operational aspects of WIG craft" started at its 40th Session in 1995 and was completed at its 46th session in 2000 with the acceptance of the "Amendments to the international regulations for preventing collisions at sea, 1972 (COLREGs-72)".

The most essential amendments read:

Rule 18:

(f) (i) A WIG craft when taking off, landing and in flight near the surface shall keep well clear of all other vessels and avoid impeding their navigation.

Rule 23:

(c) A WIG craft, only when taking off, landing and in flight near the surface, shall, in addition to the lights, prescribed in paragraph (a) of this Rule, exhibit a high-intensity all-round flashing red light.

13.6. Emerging requirements on knowledge, skill and training for officers on WIG craft

More attention has to be paid to the human factors and the relevant requirements to training and improving the qualification of the crew of a WIG craft. To this end in 2002 Australia and the Russian Federation addressed the Marine Safety Committee with a substantiated proposal (MSC 76/20/6) that the Sub-Committee on Standards for Training and Watch Keeping (STW) be entrusted to consider the issue "Requirements for knowledge, skills and training for officers on WIG craft". The Committee took a positive decision which was included in the agenda of the STW Sub-Committee.

13.7. First rules of classification and safety for small commercial ekranoplan

In the meantime the work on development, construction and testing of the first of the A-class commercial ekranoplan "Amphistar" had been completed, the vehicle being ready for subsequent serial construction and commercial operation. However, to have the legal right to such an operation the craft had to pass a special survey and be certified, i.e. to have a legal confirmation that it had been designed, constructed and equipped according to Rules in force. Therefore a question of paramount importance emerged: How to certify "Amphistar"? Thanks to the consolidation of efforts of the leading organizations of the Russian Federation and a decision taken by the Russian Maritime Register of Shipping to develop a normative basis for such type of craft, the "Temporary Rules of Classification and Safety for a Type 'A' Small Ekranoplan" appeared first in 1997, developed by the Central Scientific Research Institute of Maritime Fleet on the order and with direct participation of "Technology and Transport Ltd". One year later (in 1998) these Temporary Rules, after extensive discussions and corrections by the participating organizations and thorough consideration by the Russian Maritime Register of Shipping, were transformed into the "Rules of Classification and Construction of Type 'A' Small Ekranoplans". These Rules were adopted on January 1, 1999.

The Rules were developed on the basis of "Rules of classification and construction of sea ships of 1995", "Rules on the equipment of sea ships of 1995", "Rules of safety of craft with dynamic principles of support", "Technical requirements for small ships of the Ministry of Marine Fleet at realization of technical supervision of 1988", "International code of safety adopted by IMO resolution MSC (36) 63 of May 20, 1994" and "Basic provisions of the draft of the International Code of Safety for WIG craft (IMO document, DE 40/11/1)".

According to the definitions of the Rules: A type "A" small ekranoplan is a high-speed craft, which, when in the main operational mode (surface effect) is supported by the lift developing on an air wing (wings), using the aerodynamic influence of affinity of the water surface or other supporting surface (surface effect) and not intended for operation outside of the "surface effect" action altitude.

The Rules apply to vehicles which

- have engine power not exceeding 55 kW,
- carry not more than 12 passengers (seats only),
- operate no farther than 20 miles away from the shore and not farther than 100 miles from the place of refuge,
- operate only during day light time,
- have a maximum operational weight not exceeding 10 tons.

Thus, the work of the IMO corresponding group on the development of the requirements for ekranoplans was completed successfully, and resulted in the creation of the international normative base for design, construction and operation of ekranoplans.

14. Conclusions

The analysis of the existing information on WIG effect vehicles leads to several important conclusions based on the past immense worldwide engineering effort, with invaluable contributions and experience coming from Russian developments associated with Rostislav Alexeev and his followers.

14.1. Technical feasibility

Technical feasibility of WIG effect vehicles (possibility to develop lifting systems taking advantage of GE and able to perform stable flight in proximity to an underlying surface) has been proven both through model experiments and full size trials of prototypes.

14.2. Technical problems

The most important technical problems related to the development of WIG effect vehicles are well understood and have either been or can be solved. In particular, methods have been developed to provide static longitudinal stability, the issue which was hampering the development of the GE technology in its early days. Various liftoff aids have been developed and validated to minimize the power required for taking off the WIG effect craft, power augmentation being one of the most significant achievements in this area.

14.3. Aerodynamic configurations

Different aerodynamic configurations have been developed and examined, each of them showing advantages and disadvantages from the viewpoint of specific applications. A tendency is observed for configurations to evolve into all-wing (flying wing) or composite wing schemes, the latter being particularly advantageous from the viewpoint of efficient takeoff, aerodynamic (economic) viability in cruise and wider range of pitch stability.

14.4. Final conclusion

Whereas the early GE technology was largely associated with naval applications, today new horizons are appearing for a profound commercialization of this fast sea transport alternative. The necessary prerequisite for making this process more efficient is the further development, elaboration and international proliferation of Rules of Classification and Safety for WIG effect vehicles. Compared to the time of emergence of the technology, today there exist many new possibilities (new materials, digital automatic control systems, etc.) of making these vehicles safer and more commercially viable.

References

[1] Rozhdestvensky KV. Ekranoplans—the GEMs of fast water transport. Trans Inst Mar Eng, London 1997; 109(Part 1):47–74.

[2] Reeves JML. The case for surface effect research, platform applications and development opportunities. NATO–AGARD fluid mechnics panel (FMP) symposium in long range and long range endurance operation of aircraft, session 1A, paper no. 4, 24–27 May 1993.

[3] Rozhdestvensky KV. Aerodynamics of a lifting system in extreme ground effect. Heidelberg: Springer, 2000. p. 352.

[4] Belavin NI. Letauschie Suda-ekranoplany. Katera i Yakhty no. 15, 1968.

[5] Hooker S. Wingships: prospect for high-speed oceanic transport, Jane's all the world's surface skimmers, 1982.

[6] Hooker S. A review of current technical knowledge necessary to develop large scale wing in surface effect craft. In: Intersociety advanced marine vehicles conference, Arlington, VA, Also AIAA paper 89-1497-CP 5–7 June 1989. p. 367–429.

[7] Kaario TJ. The principles of ground effect vehicles. In: The Symposium on ground effect phenomena, Princeton University, October 1959.

[8] Wingship investigation, ARPA report, vols. 1 and 3, Arlington, 1993.

[9] Jörg GW. History and development of the 'aerodynamic ground effect craft' (AGEC) with tandem wings. In: Proceedings of the symposium "ram wing and ground effect craft". London: Royal Aeronautical Society; 19 May 1987. p. 87–109.

[10] Ando S, Miyashita J, Terai K. Design philosophies and test results of two-seated experimental simple ram wing with side floats. Kawasaki review no. 14, March 1964. p. 3–34 (in Japanese).

[11] Kirillovykh VN.Russian ekranoplans. In: Proceedings of the international workshop on twenty-first century flying ships. Sydney, Australia: University of New South Wales; 7–9 November 1995. p. 71–117.

[12] Maskalik AI, et al. ekranoplans: peculiarities of theory and design, St. Petersburg, Sudostroenie, 2000. 320c.

[13] Rozhdestvensky KV, Sinitsyn DN. State of the art and perspectives of development of ekranoplans in Russia. FAST 93 1993;2:1657–70.

[14] Sinitsyn DN, Maskalik AI. The ekranoplan is a new type of high speed water transport which can be used in all seasons. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 152–62.
[15] Ming LS, Xai LK, Hua YC, Bo N, Nai YX. Development of wing-in-ground-effect at CSSRC. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1989. p. 244–57.
[16] Li Kaixi, Ni Bo.Design and trial of the new WIG effect craft XTW-4. In: Proceedings of the 3rd international conference for high performance marine vehicles—HMPV'2000, Shanghai, 19–23 April 2000. p. 16–9.
[17] In: S.J. Phillips, editor. Jane's high-speed marine transportation, 35th ed., 2002–2003.
[18] Liang Y, Guihua P, Younong X, Jun S, Chenjie W. Research and design of dynamic aircushion wing in ground effect craft (DACWIG) type 'SWAN''. In: Proceedings of the 3rd international conference for high performance marine vehicles—HMPV'2000, Shanghai, 19–23 April 2000. p. 36–52.
[19] Fischer H, Matjasic K. From Airfisch to Hoverwing. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 69–89.
[20] Fischer H, Matjasic K. Hoverwing-technology: bridge between WIG and ACV from Airfish. In: Proceedings of the symposium on Fluid dynamics problems of vehicles operating near or in the air–sea interface. Amsterdam, The Netherlands: Research and Technology Organization; 5–8 October 1998.
[21] Ebert J, Meyer M. Hydrowing—a new efficient wing-in-ground effect craft. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 267–273.
[22] Sinitsin DN, Maskalik AI. Amphistar—first civilian ekranoplan. St. Petersburg: Sudostroenie Publishers; 2000. p. 110.
[23] Kirillovikh VN, Privalov EI. Transport amphibious platforms: a new type of high-speed craft''. In: Proceedings of the workshop ''ekranoplans and very fast craft''. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 121–33.
[24] Bennett A. Presentation on Lockheed Martin SEA concept. In: RTO/AVT symposium and specialists' meetings, Loen, Norway, 7–11 May 2001.
[25] Boeing frontiers (online), vol. 01, issue 05, September 2002.
[26] Van Beek CM, Oskam B, Fantacci G. Progress report on aerodynamic analysis of a surface piercing hydrofoil-controlled wing-in-ground effect seabus configuration. In: Proceedings of the symposium on fluid dynamics problems of vehicles operating near or in the air–sea interface. Amsterdam, The Netherlands: Research and Technology Organization, 5–8 October 1998.
[27] Gazuit G, Goupil Y. Hydrofret concept. In: Proceedings of the EuroAvia ground effect symposium EAGES 2001, SUPAERO, Toulouse, 12–15 June 2001. p. 235–46.
[28] Doctors LJ. Analysis of the efficiency of an ekranocat: a very-high-speed catamaran with aerodynamic alleviation. In: Proceedings of the international conference on wing-in ground effect craft, London, Paper no. 15, 4 and 5 December 1997.
[29] Gallington RW. Power augmentation on ram wings. In: Proceedings of the symposium 'ram wing and ground effect craft'. London: The Royal Aeronautical Society; 19 May 1987. p. 57–86.
[30] Kubo S, Matsuoka T, Kawamura T. Development of a wing in ground effect craft marine slider: μ-SKY 1 as a high speed marine boat. In: 4th Pacific congress on marine sciences and technology 1990;11:220–7.
[31] Kubo S, Matsubara T, Higashia A, Yamaguchi N, Kawamura T, Matuoka T, et al. Development of wing in surface effect craft, Marine slider μ-Sky 2 as a high speed boat for sports and pleasures. In: International marine systems design conference, May 1991. p. 155–9.
[32] Akimoto H, Kubo S, Fukushima K, Fukushima M. Development of a new wing-in-surface-effect craft for 8 passengers. In: Proceedings of FAST2001, Southhampton, UK, 2001. p. 6.
[33] Akimoto H, Kubo S, Tanaka M, Sakumasu M. Self-propulsion model test of a wing-insurface effect ship with canard configuration, Part 2. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[34] De Keyser LJ. A high-inertia slowed overhead rotor as take off aid ensures an unequaled level of safety in the operation of wing-in-ground effect (WIG) craft. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[35] Kang CG. Introduction to large WIG craft project. In: Proceedings of the 1st international symposium on WIG crafts. Seoul, Korea: Sofitel Ambassador; 8 November 2005. p. 77–84.
[36] Volkov LD, Ponomarev AV, Treschevski VN, Yushin VI. Results of aerodynamic research carried out in Krylov institute in support of design of ekranoplans. In: Proceedings of the second international conference on high speed ships, 1992.
[37] Denissov VI. Search and rescue ekranoplan SPASATEL, Sudostroenie J 1995; 1: 10–2.
[38] Aframeev EA. Conceptual bases of WIG craft building: ideas, reality and outlooks. In: Proceedings of the symposium on ''fluid dynamics problems of vehicles operating near or in the air–sea interface''. Amsterdam, The Netherlands: Research and Technology Organization; 5–8 October 1998.
[39] Nebylov AV, Sokolov VV, Tomita N, Ohkami Y. The concept of ekranoplane use for passenger aerospace plane launch and landing, transport: science, engineering, management. No. 11, 1996 (in Russian).
[40] Nebylov AV, Tomita N. Optimization of motion control at landing of aerospace plane on ekranoplan. In: 36th AIAA aerospace sciences meeting and exhibit, Reno, USA, 1998.
[41] Kubo S. Proposed operation of Orlyonok between Japan and Russia. In: Paper presented at the 2nd international conference on ekranoplans, Nizhniy Novgorod, 1994. p. 5.
[42] Sommer, G. Ekranoplan: The Soviet sea monster. In: Proceedings of the Institute of Naval Engineers, October 1988. p. 144–5.
[43] Irodov RD. Criteria of longitudinal stability of ekranoplan. Ucheniye Zapiski TSAGI, Moscow 1970;1(4):63–74.

[44] Rozhdestvensky KV. Oscillations of a wing in a gas flow close to a wall and acoustic resonance. Trudy Irkutskogo Universiteta, Asimptoticheskie Metody v Dinamike Sistem, 1982. p. 117–28.
[45] Lippisch AM. Der 'Aerodynamische Boden Effekt' und der Entwicklung des Flugflaschen (Aerofoil) Bootes. Luftfaht-technik-Raumfahrttechnik 1964;10:261–9.
[46] Fischer H. Airfoil boat technique explained on X-113 and X-114. In: International high performance vehicle conference, November 1988. p. 1–19.
[47] Bogdanov AI. The problems of ekranoplan certification. Conception and development of IMO safety requirements. In: Proceedings of the international workshop ekranoplans—flying ships of the 21st century held at the University of New South Wales, 7–9 November 1995. p. 128–47.
[48] Zhukov VI. Features of aerodynamics, stability and controllability of ekranoplans. Tsentralniy Aerogidrodinamicheskiy Institut im. Prof. N.E. Zhukovskogo, Moscow, 1997. p. 81.
[49] Rozhdestvensky KV. Characteristic features of aerodynamics of ekranoplan in extreme ground effect. Sudostroenie J 1995;1:6–8.
[50] Ermolenko SD, Rogozin YuA, Rogachev GV. Calculation of Aerodynamic characteristics of rectangular wing with end plates moving with small subsonic speed near the ground, Izvestia VUZov. Aviatsionnaya Tekh 1972(3): 105–13.
[51] Wenstedt J. Grondeeffect toestel verenigt snelheid en laadvermogen. Polytechnisch Weekblad, 16 July 1992.
[52] Avvakumov MN. Unsteady Derivatives of aerodynamic coefficients for wings of finite aspect ratio, moving near plane and wavy surface. Voprosi Sudostroeniya, Seria: Proektirovanie Sudov, Vyp. 29; 1981.
[53] Belinskiy VG, et al. Maximum and average magnitudes of hydrodynamic characteristics of the wing, moving above nonplanar ground. Gidromekhanika 1974;11(9):528–36.
[54] Efremov II, Lukaschik EP. Influence of the waves on the underlying surface upon hydrodynamic characteristics of a wing of finite aspect ratio. Trudy Chuvashskogo Universiteta, Dinamika Sploshnoi Sredy s Poverkhnostyamy Rasdela, Cheeboksary, 1982. p. 69–75.
[55] Grebeshov EP, Shakarvene EP, Tsvetkova GI. Aerodynamic characteristics of a wing in proximity of flat and wavy ground. Trudy TSAGI, Vyp. 1725, 1976. p. 3–28.
[56] Rozhdestvensky KV. Asymptotic theory of a wing, moving in close proximity to a solid wall. Izvestia AN SSSR, Mekhanika Zhidkosti i Gaza 1977(6):115–24.
[57] Maskalik AI, Rozhdestvensky KV, Sinitsyn DN. A view of the present state of research in aero- and hydrodynamics of ekranoplans. In: Proceedings of the symposium on fluid dynamics problems of vehicles operating near or in the air–sea interface. Amsterdam, The Netherlands: Research and Technology Organization, 5–8 October 1998.
[58] Besyadovskiy AR. A numerical estimation of aerodynamic characteristics and stability parameters of ekranoplans in group flight. In: Proceeding of the international conference on ground effect machines—GEM2000, St. Petersburg, 21–23 June 2000.
[59] Wieselsberger C. Wing resistance near the ground. National advisory committee for aeronautics TM 77, April 1922.
[60] Serebriysky Ya M. The Ground effect on aerodynamic characteristics of aircraft, Trudy TSAGI imeni N.E. Zhukovskogo, Vyp. 267, Moscow 1936.
[61] Plotkin A, Kennell C. Thickness induced lift on a thin airfoil in ground effect. AIAA J 1981;19:1484–6.
[62] Plotkin A, Dodbele SS. Slender wing in ground effect. AIAA J 1988;26(4):493–4.
[63] Plotkin A, Tan CH. Lifting-line solution for a symmetrical thin wing in ground effect. AIAA J 1986;24: 1193–4.
[64] Panchenkov AN. The theory of optimal lifting surface. Novosibirsk, Nauka, 1983. p. 256.
[65] Strand T, Royce WW, Fujita T. Cruise performance of channel flow ground effect machines. J Aero Sci 1962;29(6):702–11.
[66] Borst HV. The aerodynamics of the unconventional air vehicles of A. Lippisch, Henry V. Borst and Associates, Wayne, Pennsylvania, 1980, p. 280.
[67] Widnall SE, Barrows TM. An analytic solution for two and three-dimensional wings in ground effect. J Fluid Mech 1970;41(Part 4):769–92.
[68] Rozhdestvensky KV. Steady motion of a wing at vanishing distances from the ground. Trudy Leningradskogo Korablestroitelnogo Instituta, tom 80, 1972. p. 77–85.
[69] Rozhdestvensky KV. Unsteady Motion of a wing of finite aspect ratio at vanishing distances from the ground. Trudy Leningradskogo Korablestroitelnogo Instituta, tom 80, 1972. p. 69–76.
[70] Rozhdestvensky KV. Nonlinear theory of a slightly curved foil at small distances from a solid wall. Trudy Leningradskogo Korablestroitelnogo Instituta, tom 104, 1976. p. 88–95.
[71] Rozhdestvensky KV. On the problem of motion of a rectangular wing over a rigid wall. Proc Leningrad Shipbuild Inst 1977;115:62–8.
[72] Rozhdestvensky KV. On the Problem of the flow past a rectangular wing in parallel walls. Izvestia VUZov, Abiatsionnaya Tekhnika no. 4, 1978.
[73] Rozhdestvensky KV. Method of matched asymptotic expansions in ydrodynamics of wings. Sudostroenie, Leningrad, 1979. p. 208.
[74] Rozhdestvensky KV. Motion of a rectangular wing above wavy wall at arbitrary angles to the wave front. Trudy Leningradskogo Korablestroitelnogo Instituta, Gidromekhanika I Teoriya Korablya, 1979. p. 29–39.
[75] Rozhdestvensky KV. Influence of slots upon hyrdodynamic characteristics of a thin foil in steady motion near a wall. In: Proceedings of the of the seminar on boundary problems, Kazanskii Gosudarstvennii Universitet, 1979. p. 201–15.
[76] Rozhdestvensky KV. An estimate of the influence of lateral gaps upon hydrodynamic coefficients of a wing of finite aspect ratio in steady and unsteady motion near a wall. Izvestia AN SSSR, Mekhanika Zhidkosti i Gaza, 1980. p. 122–8.
[77] Rozhdestvensky KV. On the influence of endplates upon hydrodynamic characteristics of a wing in steady and unsteady motion close to a solid wall. Izvestia AN SSSR, Sibirskoye Otdelenie, Asimptoticheskie metody v Dinamike Sistem, Novosibirsk, Nauka, 1980. p. 142–8.
[78] Rozhdestvensky KV. Matched asymptotics in aerodynamics of WIG vehicles. In: Proceedings of the intersociety

high performance marine vehicles conference and exhibit HMPV 92, VA, 24–27 June 1992. p. WS 17–27.
[79] Rozhdestvensky KV. Asymptotic methods in aerodynamics of ekranoplans. In: Proceedings of the 1st international conference on ekranoplans. St. Petersburg: Marine Technical University; 3–5 May 1993. p. 81–115.
[80] Kida T, Miyai Y. A theoretical note on the lift distribution of a non planar ground effect wing. Aeronaut Q 1973;24(3):227–40.
[81] Tuck EO. Steady flow and static stability of airfoils in extreme ground effect. J Eng Math 1980(15):89–102.
[82] Tuck EO. A nonlinear unsteady one- dimensional theory for wings in extreme ground effect. J Fluid Mech 1980; 98:33–47.
[83] Newman JN. Analysis of small-aspect ratio lifting surfaces in ground effect. J Fluid Mech 1982;117:305–14.
[84] Gallington RW, Miller MK.The RAM-Wing: a comparison of simple one dimensional theory with wind tunnel and free flight results. In: AIAA paper 70-971, AIAA guidance, Control and flight mechanics conference, Santa Barbara, CA, August 1970.
[85] Rozhdestvensky KV. An effective mathematical model of the flow past ekranoplan with small endplate tip clearances in extreme ground effect. In: Proceedings of the international workshop on twenty-first century flying ships.Sydney, Australia: University of New South Wales; 7–9 November 1995. p. 155–78.
[86] Rozhdestvensky KV. Aerodynamics of a tandem of high aspect ratio/in ground effect, In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 166–84.
[87] Staufenbiel R, Bao-Tzang Y. Stability and control of ground effect aircraft in longtudinal motion. Translation, DTNSRDC report 77-0048, June 1977.
[88] Kumar PE. An experimental investigation into the aerodynamic charactersistics of a wing with and without endplates in ground effect. College of aeronautics report, Aero 201, 1968.
[89] Staufenbiel R, Yeh BT. Flugeigenschaften in der Laengsbewegung von Bodeneffekt-Fluggeraeten, Teil I and II, ZFW, vol. 24. January/February 1976. p. 3–9; and March/April 1976. p. 65–70.
[90] Staufenbiel R. Flugeigenschaften von Bodeneffekt-Fluggeraeten. Zeitschrift fur Flugwissenschaften, vol. 24, Hefte 1, 2, January–Febrauary 1976. p. 3–9, March/April. p. 65–70; English Trans. "Stability and control of ground effect aircraft in longitudinal motion", DTNS RDC 77-0048, June 1977; 1976.
[91] Staufenbiel R. Some nonlinear effects in stability and control of wing in ground effect vehicles. J. Aircraft August 1978; 15.
[92] Staufenbiel R, Kleineidam G. Longitudinal motion of low-flying vehicles in nonlinear flowfields. In: Proceedings of the congress of the international council of the aeronautical sciences, Munich, FRG, 1980. p. 293–308.
[93] Staufenbiel RW. On the design of stable ram wing vehicles. In: Proceedings of the symposium ram wing and ground effect craft. London: The Royal Aeronautical Society, 19 May 1987. p. 110–36.
[94] Staufenbiel R, Schlichting UJ. Stability of airplanes in ground effect. J Aircraft 1988;25(4).
[95] Zhukov VI. Some matters of longitudinal stability of ekranoplans. Moscow: Trudy TSAGI; 1974.
[96] Taylor G. Wise up to a WIG. Mar Model Mon June 1995.
[97] Kleineidam G. Ein Beitrag zur Untersuchung der Aerodynamischen und Flugmechanischen Eigenschaften von Profilen in Bodennahe. Dissertation, RWTH, Aachen, FRG. 1981.
[98] Gadetski VM. Investigation of aerodynamic characteristics of the foil with control devices near the ground. Trudy TSAGI, M., Vyp. 1256, 1970. p. 2.
[99] Arkhangelski VN, Konovalov SI. Computational investigation of the influence of parameters of the foil upon its aerodynamic characteristics near the ground, Trudy TSAGI, vyp. 2304, M., 1985. p. 12–21.
[100] Plissov NB, Rozhdestvensky KV, Treshkov VK. Aerodynamics of high speed ships with dynamic support, Leningrad, Sudostroenie, 1991. p. 247.
[101] Kornev NV. Problems of stability of ekranoplans. In: Proceedings of the workshop on WIG ship technology. Yusung, Korea: Korea Research Institute on Ships and Ocean Engineering, 1–6 June 1995. p. 10.
[102] Shin MS, et al. Wind Tunnel test results for eight and twenty passenger class wing in ground effect ships. In: Proceedings of the FAST'97, Sydney, July 1997.
[103] Rozhdestvensky KV. Stability of a simple lifting configuration in extreme ground effect. In: Proceedings of the international conference on wing-in-ground-effect craft (WIGs), Paper no 16. London: The Royal Institution of Naval Architects, 4 and 5 December 1997.
[104] Onspaugh CM. Wind tunnel investigation of single and tandem low aspect ratio wings in ground effect. Report LFL L-53, Lockheed Aircraft Corporation, California Division, May 1963.
[105] Jörg GW. Tandem aerofoil flairboats (TAF). In: Proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 3, 4 and 5 December 1997.
[106] Sokolov VV. A new generation of flying ships. Sudostroenie 1991(638):3–7.
[107] Rozhdestvensky KV. Theoretical analysis of dynamics of a WIG Vehicle in extreme ground effect. In: Proceedings of the symposium on fluid dynamics problems of vehicles operating near or in the air–sea interface. Amsterdam, The Netherlands: Research and Technology Organization; 5–8 October 1998.
[108] Zhukov VI. Particular features of aerodynamics of ekranoplan. In: Proceedings of the 1st international conference on ekranoplans. St. Petersburg: Marine Technical University; 3–5 May 1993. p. 23–36.
[109] Fink MP, Lastinger JL. Aerodynamic characteristics of low-aspect-ratio wings in close proximity to the ground. NASA TN D-926, July 1961.
[110] Alexeyev SS. Creation of high-speed amphibious boats using ground proximity effect on the example of SEVER boats. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 134–45.
[111] Cheremukhin O. An air-cushion take-off and landing device for aircraft and ekranoplans. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 247–62.

[112] Fischer H, Matjasic K. The Hoverwing technology-bridge between WIG and ACV. In: Proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 5, 4 and 5 December 1997.
[113] Muller W. Abbildungstheoretische Grundlagen fur das Problem des Tragflugels in Bodennahe, ZMM, 1931.
[114] Murao R, Seki S, Tomita N. On a study of a WIG with propeller-deflected slipstream (PDS) by using a radio-controlled model. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[115] Kravchuk SV, et al. Flying over waves (ekranoplan 'Orlyonok'). Aviat J Aerohobby, 1992; 2: 2–10.
[116] Fischer H. Base of experience in ground effect—Fischer Flugmekhanik. In: Proceedings of the WIG meeting, organized by Techno Trans e.V., Rostock, Germany, 29–30 September 1995.
[117] Diomidov VB. Automatic control of motion of ekranoplan. Electropribor, Saint-Petersburg, 1996. p. 51.
[118] Akagi S. Synthetic aspects of transport economy and transport vehicle performance with reference to high speed marine vehicles, FAST 91, Trondheim, Norway, vol. 1. 1991. p. 277–92.
[119] Bogdanov AI, Maskalik AI. Some results on the civil ekranoplans certification works. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 177–85.
[120] Kuteinikov MA, Gappoev MA, Gadalov VV. Wing-in-ground effect (WIG) craft (ekranoplan) general safety aspects as contained in the international instruments and RS rules. Perspectives. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[121] Pustoshniy A, Anosov V, Ganin S. Some remarks on WIG development in Russia and state of the art with WIG regulations and designing. In: Proceedings of the 1st international symposium on WIG crafts. Korea: Sofitel Ambassador Seoul, 8 November 2005. p. 7–13.
[122] Rules of classification and construction of small ekranoplans of type A. St. Petersburg, Russian Maritime Register of Shipping, 1998.

Further reading

[123] Ackermann V. Zur Berechnung der Aerodynamischen Beiwerte und des Stromungsfeldes von Tragflugeln in Bodennaehe unter Berücksichtigung von Nichtlinearitäten, Dissertation, Darmstadt, 1966.
[124] Adler C, Coopersmith R. An investigation using an aerodynamic panel code, of a special case of a wing flying in close proximity to a water surface. AIAA paper 951845, 1995.
[125] Aerofoil: Marine 'Schiff' der Zukunft?, Wehrtechnik no. 11, November 1975. p. 642.
[126] Agarwal RK, Deese JE. Numerical solutions of the Euler equations for flow past an airfoil in ground effect. AIAA paper 84-0051, 1984.
[127] Agarwal RK, Deese JE. Aerodynamics of an airfoil in ground effect with a jet issuing from its underside. AIAA paper no. 0019, 1985. p. 8.
[128] Afremov AS, Nikolaev EP. Prediction of the Dynamic performance for high-speed marine vehicles, problems of hydrodynamics. St. Petersburg; Krylov SRI: 1994.
[129] Afremov A Sh, Zhitmuk AP, Nikolaev EP, Smolina NA. Hydrodynamics of ekranoplanes. In: Proceedings of the international conference on 300th anniversary of the Russian navy NAVY AND SHIPBUILDING NOWADAYS, Saint-Petersburg, Russia, 26–29 February 1996. p. A2-5-1–10.
[130] Afremov AS, Smolina NA, Zhitnyuk WIG, Hydrodynamic problems. In: The proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 154–65.
[131] Ailor WH, Eberle WR. Configuration effects on the lift of a body in close ground proximity. J Aircraft, AIAA 1975;13(8).
[132] Airfoil-flairboats just above sea surface. Hansa-Schiffahrt-Schiffbau-Hafen, 1991. p. 28–40.
[133] Akimoto H, Kubo S, Yamagata A. Wing characteristics of three profiles in surface effect using a simulation at a high Reynolds number. In: The proceedings of the international workshop WISE up to ekranoplan GEMs, Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 185–90.
[134] Akimoto H, Kubo S, Taketsune T. A new concept of wing-in-surface-effect ship. In; Proceedings of China international boat show and high performance marine vehicles (HPMV) conference 2003, E9.
[135] Akimoto H, Kubo S, Kawakami M, Tanaka M. Canard type wing-in-surface effect ship: self propulsion model and a conceptual design. In: Proceedings of the 1st international symposium on WIG crafts, Sofitel Ambassador Seoul, Korea, 8 November 2005. p. 55–65.
[136] Amkhanbitskiy RYa, Chernyavets VV. Selection of routes of transport and passenger Ekranoplans. Sudostroenie 1994(5–6):4–5.
[137] Ando S, Miyashita J, Terai K. Summary of the model tests for simple ram wing KAG-3, hovering craft and hydrofoils. Kawasaki Aircraft Co., August–September 1964.
[138] Ando S. An idealized ground effect wing. Aeronaut Q 1966;XVI:53.
[139] Ando S. Minimum induced drag of ground effect wings. J Hydronaut 1975;10(3):106–12.
[140] Ando S. Minimum Induced drag of non-planar ground effect wings with small tip gaps. J Jpn Soc Aero Space Sci 1975;23(256):304–11.
[141] Ando S, Yashiro H. Minimum induced drag of ground effect wings. J Hydronaut 1975;10(3).
[142] Ando S. Minimum induced drag of ground effect wings. J Hydronaut 1976;10(3):106–12.
[143] Ando S. Some thoughts on power-augmented ram wing-in-ground (PAR-WIG) effect. In: AIAA/SNAME advanced marine vehicles conference, 1979.
[144] Ando S. Introduction to WIG craft, 1989 (in Japanese).
[145] Ando S. The role of WIG effect vehicles in the transport industry. Fast Ferry International, April 1990. pp. 33–8.
[146] Ando S. Critical review of design philosophies for recent transport WIG effect vehicles. Trans Jpn Soc Aeronaut Space Sci 1990;33(99):29–47.

[147] Ando S, Kato M. PAR-WIG performance during acceleration from water-borne to air-borne. Trans Jpn Soc Aeronaut Space Sci 1991;34(105):139–52.
[148] Ando S, Ishikawa M. Aerodynamics of a thin airfoil flying over and in proximity to a wavy wall surface-lifting surface theory. Trans Jpn Soc Aeronaut Space Sci 1991;34(103): 1–11.
[149] Ando S. Note on prediction of aerodynamic lift/drag ratio of WIG at cruise. FAST 93 1993;2:1657–70.
[150] Ando S. A systematic computation scheme of PARWIG cruising performance. Trans Jpn Soc Aeronaut Space Sci 1993;36(112):92–106.
[151] Ando S. Some topics for WIG (ekranoplan) design. In: Proceedings of the workshop on high- speed marine craft. Korea Research Institute on Ships and Ocean Engineering, September 1995. p. 3–8.
[152] Ando S. Some topics on WIG (ekranoplan) design. Jpn Soc Aerospace Sci 1996;39.
[153] Ando S. Design philosophy of PARWIG for commuter transport. In: Proceedings of the international conference on wing-in-ground effect craft, Paper no. 6, London, 4–5 December 1997.
[154] Ando S. A systematic computation scheme for PAR-WIG cruising design point. J Jpn Soc Aerospace Sci 1997;39.
[155] Andrich D. The demonstrator WIG craft of type HYDROWING: development, design and test trials. In: Proceedings of the 1st international symposium on WIG crafts, Sofitel Ambassador Seoul, Korea, 8 November 2005. p. 27–46.
[156] A new type of aircraft, Neva News, vol. 2(22). 15–30 November 1993, p. 8.
[157] Armstrong NA, Harrod D. On the safety of navigation above the sea. In: Proceedings of a workshop on twenty-first century flying ships. Sydney, Australia: The University of New South Wales; 7–8 November 1995. p. 118–27.
[158] Artigiani R, Harper GP. The flying frigates. In; Proceedings of the US Naval Institute, June 1983. p. 55–9.
[159] Ashill PR. The state of the art of ram-wing research. Hover Craft Hydrofoil 1963;2:18–22 May.
[160] Ashill PR. Kawasaki KAG-3, Air-cushion vehicles, February 1964. p. 29–30a.
[161] Ashill PR. On some aspects of the aerodynamic performance of ground effect wings. PhD thesis, Southhampton University, June 1968.
[162] Ashill PR. On the aerodynamic design of wings in ground effect. Fluid Dynam Trans 1969;4:677–87 Warszawa.
[163] Ashill PR. On the minimum induced drag of ground effect wings. Aeronaut Q 1970;XXI:211 August.
[164] Avvakumov MN, Volkov LD, Ganin SM, Treschevsky VN, Yushin VI. Special methods for experimental and theoretical investigations of aerodynamics in support of design of ekranoplans. In: Proceedings of the international conference 300th anniversary of the Russian Navy NAVY AND SHIPBUILDING NOWADAYS, 26–29 February, St. Petersburg, Russia, 1996. p. A2-6-1–7.
[165] Avvakumov MN, Volkov LD, Ponomarev AV. WIG flight safety problems. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales, 15–16 June 1998. p. 138–44.
[166] Avvakumov MN, Volkov LD. Development of methods of safe handling of ekranoplan based on computer simulation of its motion'. In: Proceedings of the 2nd international shipbuilding conference—ISC''98, St. Petersburg, Russia, 24–26 November 1998. p. 392–98.
[167] Bagley JA. Low speed wind-tunnel tests on a two-dimensional aerofoil with split flap near the ground, ARC CP 568, 1961.
[168] Bagley JA. The pressure distribution on two-dimensional wings near the ground. Aeronautical Research Council, R&M 3238, 1961.
[169] Baker PA, Schweikherd WG, Young WR. Flight evaluation of ground effect on several low-aspect ratio airplanes. NASA TN D-6063, October 1970.
[170] Balow FA,Guglielmo JG, Sivier KR. Design and evaluation of a midsize wing-in-ground effect transport. In: AIAA 93-3952, AIAA Aircraft design, systems and operations meeting, Monterey, CA, 11–13 August 1993.
[171] Balow F, Guglielmo J, Trzesbiak M, Zacko T. SeaSkimmer II, AAE 391KRS Advanced design final report. The University of Illinois at Urbana-Champaign, 1993.
[172] Barber T, Leonardi E, Archer D. Appropriate CFD technique for the prediction of ground effect aerodynamics. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 55–68.
[173] Barber T, Leonardi E, Archer D. Free surface deformation caused by a wing in ground effect over water. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia, The University of New South Wales: 15–16 June 1998. p. 90–101.
[174] Barber T. A Study of the aerodynamic characteristics of ground effect flight. PhD thesis. Australia: University of New South Wales; 2000.
[175] Barber T. Free surface deformations caused by a moving wing in ground effect flying over water. In: Proceedings of the PACIFIC 2004 international maritime conference, vol. 1. Session 11-WIGs, 2004. p. 356–65.
[176] Barkley WB. Hydrodynamic force and spray tests on wing end plates penetrating water surface. General dynamics/ Convair report no. 64100, San-Diego, CA, 1964.
[177] Barrows TM, Widnall SE. Optimum lift–drag ratio for a ram-wing tube vehicle. AIAA J 1970;8(3):491–7.
[178] Barrows TM, Widnall SE, Richardson HH. FRA-RT-71-56, 1970.
[179] Barrows TM, Widnall SE. The aerodynamics of ram-wing vehicles for application to high-speed ground transportation. In: The 8th aerospace science meeting, New York, AIAA paper 70-142, 1970.
[180] Bartini RL. Tomorrow's transport. Sovetskiy Souz 1974(12):50–1.
[181] Basin MA, Shadrin VP. Hydrodynamics of wings in proximity to the interface of two media. Sudostroenie, Leningrad, 1980. p. 304.
[182] Basin M, Kramerov E, Latorre R. WIG (ekranoplane) as a transport vessel and sport craft. In: proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 74–5, December 1997.
[183] Basin M, Kipin A, Kramerov E. Flying sport craft. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 223–40.
[184] Belavin NI. Ekranoplans, Leningrad, Sudostroenie, 1968, 1977. p. 230.

[185] Belavin NI. Super-large ekranoplans of chief designer R.E. Alexeev, Sudostroenie 1993(1):3–7.
[186] Belinskiy VG. Motion of an inclined wing close to a surface. Gidrodinamika Bolshikh Skorostei no. 4, Kiev, 1968.
[187] Belinskiy VG, Laptev YuI. Motion of a wing with deflected ailerons close to a surface. Gidrodinamika Bolshikh Skorostei no. 4, Kiev, 1968.
[188] Belinskiy VG, et al. Effect of the form of a nonplanar screen on the hydrodynamic characteristics of a foil traveling above it. Gidromekhanika 1975(31):28–32 Kiev.
[189] Belinskiy VG, et al. Effect of Strouhal number on foil characteristics near a wavy screen. Gidromekhanika 1975(32).
[190] Belinskiy VG, Orichishev VA. On the efficiency of a flap near a solid wall. Gidromekhanika, Kiev 1985;52:58–62.
[191] Belinskiy VG, Zinchuk PI. Hydrodynamic characteristics of an ekranoplane wing flying near the wavy surface. In: Proceedings of the symposium on fluid dynamics problems of vehicles operating near or in the air–sea interface. Amsterdam, The Netherlands: Research and Technology Organization; 5–8 October 1998.
[192] Belotserkovsky SM. Calculation of the flow past a wing of arbitrary planform in a wide range of angles of attack, No. 4. Izvestia AN SSSR, Mekhanika Zhidkosti i Gaza, 1968.
[193] Belotserkovsky SM, Skripach BK. Aerodynamic derivatives of a flying vehicle and a wing at subsonic speeds. Moscow: Nauka; 1975. p. 312.
[194] Belotserkovsky SM, Skripach BK, Tabachnikov VG. A wing in unsteady gas flow. Moscow: Nauka; 1975.
[195] Belotserkovsky SM, Nisht NI. Separated and non-separated ideal fluid flow past thin wings. Nauka Publishers: Moscow; 1978.
[196] Belyaev AA. Magic flight. Moscow: Avico Press; 1993.
[197] Beriev G, Bogatyrev A. Flying ocean liners, Aviatsya i Kosmonavtika, 1973.
[198] Berkovskiy BS, Koshevoi VI. Motion of a thin airfoil at arbitrary distances from a solid boundary. Gidrodinamika Bolshikh Skorostei, No. 1, 1965. p. 21–32.
[199] Berkovskiy BS. Calculation of the characteristics of a lifting system with elastic elements. Kiev: Gidrodinamika Bolshikh Skorosteiy; 1967.
[200] Berkovskiy BS. Stationary motion of an elastic contour in a bounded fluid. Prikl Mekh 1987;3(11).
[201] Bertelsen WR. The aircopter GEM project, hovering craft and hydrofoil, July 1962. p. 21.
[202] Bertin J. Une Nouvelle Aviation de Transport Lourde (a unique large transport aircraft), no. 46, 1973–1974. p. 2–8.
[203] Besekersky VA, Diomidov VB, Yarovoi EI. Dynamic system of a ship—ekranoplan with accout of elasticity of its hull, Morskoye Priborostroenie, Ser. 11, vyp. 3, 1972.
[204] Bessho M, Ishikawa A. On the water surface effect on an air wing (1st Report). Trans West-Jpn Soc Naval Archit 1992;83.
[205] Besyadovskiy AR, Plissov NB, Treshkov VK. Experimental investigation of the vortex system behind a wing moving over the surface of water. Trudy Leningradskogo Korablestroitelnogo Instituta 1976(104).
[206] Besyadovskiy AR, Kornev NV, Treshkov VK. Numerical method of calculation of aerodynamic characteristics of ekranoplan. In: Proceedings of the 1st international conference on ekranoplans. St. Petersburg: Marine Technical University; May 3–5 1993. p. 48–65.
[207] Betts CB, Clayton BR. A possible future for surface effect craft in the UK. In: Proceedings of the symposium ram wing and ground effect craft. London: The Royal Aeronautical Society; 19 May 1987. p. 137–74.
[208] Betz A. Auftrieb und Widerstand einer Tragflaeche in der Naehe einer Horizontal-Ebene, ZFM, no. 17, 1912.
[209] Betz A. The lift and drag of a wing in proximity to the ground. McCook Field memorandum no. 167, 1912.
[210] Biner I. Ekranoplan Danger outweigh benefits, Engineers Australia, February 1996.
[211] Binder G. Nichtlineare Tragflaechentheorie fuer schiebende und haengende Fluegel in Bodennaehe. Z Flugwiss Weltraum 1977;1(4):241–50.
[212] Bippes H, Turk M. Windkanalmessungen an einem Rechteckflugel kleiner Streckung in Bodennahe, Parts I and II, DFVLR-IB 222-81 Ao3, 1981 and DFVLR-IB 222-82 A10, 1982.
[213] Blinov, Ekranoplan, Izobretatel I Ratsionalizator, no. 3, 1965. p. 18–9.
[214] Blyth A. Wing-in-ground-effect craft- the ultimate fast ferry? Fast Ferry International, June 1993. p. 32.
[215] Boeckh M. Monster des Kaspischen Meeres ist enttarnt, Die Welt, 10 November; 1995.
[216] Boeder P. Met de fliegboot in een kwartier over het kanaal, Technisch Weekblad, 26 April 1995. p. 6.
[217] Bogdanov AI, Sinitsyn DN. New IMO high-speed craft code and the problems of ekranoplan certification, FAST 93, vol. 2, Yokohama, Japan, 13–6 December; 1993. p. 1457–64.
[218] Bogdanov AI, Sinitsyn DN. Development of a new IMO high-speed craft safety code and the problems of certification of ekranoplans. In: Proceedings of the 1st international conference on ekranoplans, Marine Technical University, St. Petersburg, 3–5 May 1993. p. 66–71.
[219] Bogdanov AI. Safety providing rules development-actual task of present stage of transport ekranoplans development. In: Proceedings of the 2nd international conference on ekranoplans, Russia, Nizhniy Novgorod, 1994.
[220] Bogdanov AI. Development of IMO safety requirements for a new high-speed sea-going transportation WIG craft—present state. FAST 95, no. 1. Germany: Lubeck-Travemunde; 25–27 September 1995. p. 631–9.
[221] Bogdanov AI, Zhukov VI. The setting of a ground effect action altitude in the new international code of WIG Craft safety. In: Proceedings of the international workshop on ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 186–93.
[222] Bogdanov AI. Discussions on the operational aspects of WIG Craft at the IMO Sub-committee on safety of navigation. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 213–29.
[223] Bogdanov AI, Peresypkin V. Operational aspects of WIG craft possible amendments to COLREGs. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 145–53.

[224] Bogdanov AI. The first international requirements to safety of a wing-in-ground effect craft. In: Proceedings of the PACIFIC 2004 international maritime conference, no. 1, Session 11-WIGs, 2004. p. 330–45.
[225] Bogdanov AI. Perspectives of application in the Arctic's regions of the newest amphibian vehicles, utilizing ground effect. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[226] Bolt S. Kaspisch zeemonster te koop, Kijk, April 1995, p. 78–81.
[227] Boot en vliegtuig tegelijk: Flairboat, Motorboot, April 1991, p. 30–31.
[228] Borisuk MN, Ezhov VM, Sterkhov AP. Motion of a lifting surface near a solid boundary. Gidrodinamika Bolshikh Skorostei, Cheboksary, 1981. p. 25–36.
[229] Borst HV. Analysis of vehicles with wings operating in ground effect. In: AIAA/SNAME advanced marine vehicles conference, Baltimore, Maryland, 2–4 October 1979.
[230] Borst HV. The aerodynamics of unconventional air vehicles of A. Lippisch. Pennsylvania, USA: Henry V. Borst & Associates; 1980.
[231] Brown JR. Wind-tunnel investigation of single and tandem low aspect ratio wings in ground effect. TRECOM TR-63-63, March 1964.
[232] Brown JR, Stevens WP, Onspaugh CM, et al. Wind-tunnel investigation of single and tandem low aspect ratio wings in ground effect. Lockheed report no. 16906, 1964.
[233] Bry WA, Walker RL, Smith GR. An analysis of the performance and stability characteristics of PAR-WIG CRDKNWC/RD-22-93/99, Carderock Division, Naval Surface Warfare Center, Bethesda, Maryland, April 1993.
[234] Buell DA, Tinling BE. Ground effects on the longitudinal characteristics of two models with wings having low aspect ratio and pointed tips. NACA TN-4044. 1957.
[235] Buivol VN, Ryabokon VA. On the problem of flutter of a wing near the screen. Gidromekhanika, Respublikanskiy Mezhvedomstvenniy Sbornik, Kiev, Naukova Dumka,Vyp. 5, 1968. p. 35–44.
[236] Bustin I. The ekranoplane–Russian Wingship Technology Naval Forces, no. 5, 1992. p. 81–8.
[237] Butler SFI, Moy BA, Pound TN. A moving-belt rig for ground simulation in low-speed wind tunnels. ARC, R&M, no. 3451, 1967.
[238] Butlitski AG, Maskalik AI, Tomilin VV, Lukjanov AI. Experience and operation safety of the first small civil ekranoplan of type A "Aquaglide". Value of its creation for the further development of ekranoplan building. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[239] Bylinsky G. A great plane that rides the waves. FORTUNE, 10 February 1992. p. 117.
[240] Calkins DE. A feasibility study of a hybrid airship operating in ground effect. J Aircraft 1977;14:809–15.
[241] Cameron K. The boat that flies. Popular Science, April 1992. p. 57–60, 111.
[242] Carter AW. Effect of the ground proximity on the aerodynamic characteristics of aspect ratio 1 airfoils with and without end plates. NASA TN D-970, October 1961.
[243] Chang RC, Muirhead VU. Investigation of dynamic ground effect. NASA CP-2462, 1985.
[244] Chang RC, Muirhead VU. Effect of sink rate on ground effects of low aspect ratio wings. AIAA J Aircraft 1987;l:24.
[245] Chang CH, et al. Design and construction of a 1.8 m sized radio controlled PARWIG craft. In: Proceedings of the autumn meeting. Seoul: Society of Naval Architects of Korea; 1996. p. 109–13.
[246] Chaplin HR. Ground effect machine research and development in the United States, In: Naval hydrodynamics symposium, September 1960. p. 271–306.
[247] Chaplin HR, McCabe Jr. EF, Berman HA, Smithey JH. Capture of an axi-symmetric free jet in a pipe with application to power-augmented-RAM Wing Theory, David W. Taylor Naval Research and Development Center, Aviation and Surface Effect Department, Report No. DTNSRDC/ASED-79/12, December 1979.
[248] Chawla MD. Wind tunnel investigation of wing-in-ground effects. In: Collection of technical papers, AIAA 6th applied aerodynamics conference, 1988.p. 147–53.
[249] Chebotaev VF. A wing of small aspect ratio with endplates in bounded fluid. In: Gidrodinamika i matematicheskie tekhnologii, Trudy Gorkovskogo Politekhnicheskogo Insituta, 1988. p. 94–100.
[250] Chen YS, Schweikhard WG. Dynamic ground effects on a two-dimensional flat plate. J Aircraft 1985;22: 638–40.
[251] Chubikov BV, Pashin VP, Treshchevsky VN, Maskalik AI. ekranoplan—a high speed marine vehicle of new type. In: Proceedings of the international conference FAST'91, Trondheim, 1991.
[252] Chun HH, Park IR. Analysis of steady and unsteady performances for 3-D airwings in the vicinity of the free surface. In: Proceedings of the international workshop ekranoplans—flying ships of the 21st century held at the University of New South Wales, 7–9 November 1995, p. 23–46.
[253] Chun HH, et al. Experimental studies on WIG Effect and design and construction of a PARWIG craft. In: Proceedings of the 95th autumn meeting of the Society of Naval Architects of Korea, 1995. p. 239–44.
[254] Chun HH, Park IR, Chung KH, Shin MS. Computational and experimental studies on wings in ground effect and a WIG effect craft. In: Proceedings of the international workshop on ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 38–59.
[255] Chun HH, et al. Experimental investigation on wing in ground effect. In: Proceedings of the 3rd Korea–Japan workshop on ship and marine hydrodynamics, Dajeon, Korea, 4–5 July 1996.
[256] Chun HH, Chung KH, Chang JH. Smoke trace flow visualization of a wing in vicinity of the ground. In: Proceedings of the 2nd Japan–Korea joint symposium on advanced technologies, Yokohama, Japan, October 31–November 2 1996.
[257] Chun HH, Chung KH. Performance analysis of wing in ground effect craft. In: Proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 14, 4–5 December 1997.
[258] Chun HH, et al. Preliminary design of a 20 passenger PARWIG craft and construction of a 1/10 scale radio controlled model. In: Proceedings of the FAST'97, Sydney, July 1997.

[259] Colon A. Formulation of correct collision avoidance safety regulations: radar detection vs. ekranoplan climb dynamics. In: Proceedings of the international workshop on ekranoplans and very fast craft, Sydney, Australia: University of New South Wales; 5–6 December 1996. p. 258–71.
[260] Cook N. Caspian monster tale confirmed, Jane's Defence Weekly, 28 September 1991. p. 550.
[261] Cook N. Missile armed WIG confirmed by video, Jane's Defence Weekly, 12 June 1993.
[262] Comisarov P, Brasseur G. An evaluation of the wing-in-ground effect (WIG) Transport aircraft concept. DTMB report C2318, November 1966.
[263] Cowley WL, Lock CNH. Cushioning effect on aeroplanes close to the ground. RSM no. 759, British ARC, 1920.
[264] Cruising at 180 km/h, small craft, December 1986, p. 118–9.
[265] Cross NH. The third level: operational considerations. In: Proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 11, 4–5 December 1997.
[266] Cui EJ. Advances and problems in WIG vehicle research and application. In: Proceedings of China international boat show and high performance marine vehicles (HPMV) conference 2003 E15, 2003.
[267] Czerniawski S. Ekranoloty ZSRR (screen planes of the USSR), Skrzydlata Polska, 14 August 1977. p. 8–9.
[268] Dane A. Wingships, popular mechanics, May 1992. p. 35–38, 123.
[269] Danilchenko K. On the Influence of the jet upon a circular wing near a solid boundary. Prikl Mekh 1971(9):124–9.
[270] Daetwyler G. Untersuchungen ueber das Verhalten von Tragfluegelprofilen sehr nahe am Boden. Mitteilungen aus dem Institut fuer Aerodynamik, E.T.H., Zuerich, 1934.
[271] Day AH, Doctors LJ. A study of the efficiency of the wing-in-ground effect concept. In: Proceedings of the workshop on twenty-first century flying ships. Sydney, Australia: The University of New South Wales; 7 and 8 November 1995. p. 1–22.
[272] de Haller P. La Portance et la Trainee Induite Minimum d'une Aile au Voisinage du Sol, Mitteilunger aus dem Institut fur Aerodynamik der Technischen Hochschule, Zurich no. 5, 1936.
[273] Deese JE, Agarwal RK. Euler calculation for flow over a wing in ground effect. AIAA paper 86-1765 CP, 1986.
[274] Degtyarev GL. Main results of research within the international scientific—technical program ekranoplan, Aviatsionnaya Tekhnika, Moscow, no. 2, 1995.
[275] Defence publication depicts new Soviet military aircraft. Aviat Week Space Technol 7 April 1986; 121.
[276] Dessi D, Giorgi A, Morino L, Bernandini G, Puorger PC. Steady and unsteady loads on airfoils in ground effect and marine applications. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[277] Design Bureau Privatises. Aviat Week Space Technol 26 April 1993; 64.
[278] Ding HA. Development of an amphibian wing in ground effect craft. In: Proceedings of the international high performance vehicle conference, Shanghai, China, 1988.
[279] Doctors L. Air-cushion vehicles and ekranoplans: flying ships of the future. Marinet News (Newslett Aust Mar Ind Network 8 October 1995; 1–3.
[280] Doctors LJ. Parametric investigation of the influence of the geometry of an ekranocat on its performance. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 29–46.
[281] Dodds H. Looking for a buyer: the Caspian Sea monster. Jane's Intel Rev December 1991; 554–8.
[282] Douglas report no.SM-22615, 1956
[283] Douglas Aircraft Company, Wing-in-ground effect vehicles, June 1977.
[284] Dragos L. Subsonic flow past a thick wing in ground effect, lifting line theory. Acta Mech 1990; 49–60.
[285] Dragos L. A numerical solution of the equation of thin foil in ground effect. AIAA J 1990; 28.
[286] Druenen R.van. Wie maakt van de vliegboot een succes, Kiik, August 1987. p. 14–7.
[287] Duitsers testen prototype vliegboot op IJsselmeer, Schuttevar, 6 October 1990.
[288] Eaton PT. A method for predicting the static aerodynamic characteristics of low aspect ratio configurations. DTMB report no. 2216, June 1966.
[289] Ebersolt M, Unteresteller LP. L'Engine a l'Effet de Sol Naturel. Bull l'Assoc Tech Maritime Aeronaut, Paris 1974; 74: 263.
[290] Edwards LC. Experimental study of wing-in-ground effects in the AFIT 5-foot wind tunnel. MS thesis, AFIT/GAE/AA/87M-1. School of Engineering, Air Force Institute of Technology, Wright Patterson Air Force Base, OH, March 1987.
[291] Ekranovoz-Ekranolyot, Gudok, 29 September 1974 and the 'Red Baron', Nedelya, no. 42, 16–22 October 1972 (Interviews with Robert Lyudvigovich Bartini).
[292] Ekranoplans—will they take off?, Engineers—Australia, vol. 67(12), December 1995, p. 26–9.
[293] Efremov II. Influence of compressibility of aerodynamic characteristics of a wing, moving above the surface of incompressible fluid. Dinamika Tverdikh i Zhidkikh Tel. no. 63–5, 1965.
[294] Efremov II. Unsteady Motion of a thin foil near an interface of fluids of different densities. Gidrodinamika Visokikh Skorostei, Kiev, Naukova Dumka, No. 1, 1965. p. 49–65.
[295] Efremov II. To the problem of unsteady motion of a thin foil near the interface. Gidromekhanika, Kiev, Naukova Dumka, vyp. 15, 1969. p. 29–34.
[296] Efremov II. On interaction of the vortex wake with the ground. Gidrodinamika Vysokikh Skorostei, Leningrad, Sudostroenie 318: 1975; 45–55.
[297] Efremov II. Oscillations and stability of an elastic plate in an incompressible flow near a solid boundary. Gidromekhanika, Kiev, Naukova Dumka 1981(43):29–34.
[298] Efremov II, Lukaschik EP, Unov SV. Unsteady subsonic flow around a thin foil near a rigid boundary. Trudy Konferentsii po Gidrodinamike Vysokih Skorostei and Granichnym Zadacham: abstracts, Krasnodar, 1982. p. 15.
[299] Efremov II, Lukaschik EP. On unsteady motion of thin wings in proximity of a flat and solid boundary. Trudy Irkutskogo Universiteta, Asymptoticheskie Metody v Teorii System, 1983. p. 128–37.
[300] Efremov II. Problems of aerodynamics of flexible lifting surfaces. Asimptoticheskiye Metody v Teorii Sistem, Irkutsk 1983:48–79.

[301] Efremov II, Lukaschik EP. On unsteady motion of thin wings near a flat solid boundary. Asimptoticheskiye Metody v Teorii Sistem, Irkutsk 1983:128–37.
[302] Efremov II. On the method of separation of solutions in 'quadrupole theory' of the wing, Dinamika sploshnoi sredy s nestatsionarnimy granitsami Cheboksary 1984; 53–8.
[303] Efremov II, Unov SV. Harmonic oscillations of a thin foil in subsonic flow near a boundary. Trudy OIIMF. Wave Motions Fluids: Theory Exp 1984:59–64.
[304] Efremov II. Unsteady characteristics and hydroelasticity of thin wings near interfaces. Dissertation of Doctor of Sciences, Kiev, 1985.
[305] Efremov II, Lukaschik EP. Mathematical model of motion of a wing above the wavy solid wall. Gidromekhanika, Kiev 1986(53):3–7.
[306] Efremov II, Naumova EI. Oscillations of an elastic plate near a solid boundary of compressible fluid. Aktualniye Voprosy Teorii Kraevykh Zadach i Ikh Prilozheniya, Cheboksary, 1988. p. 76–85.
[307] Efremov II. Oscillations and stability of an elastic plate in incompressible flow near a rigid wall, Gidrodinamika, no. 43. Kiev: Naukova Dumka; 1991. p. 29–34.
[308] Efremov II, Lukaschik EP, Huako NM. Oscillations of a thin plate in compressible fluid near a solid boundary. Problems of applied mathematics and mechanics. Proc Sci Res Work 1994;1:64–8 Krasnodar.
[309] Efremov II, Huako NM. Transitional aerodynamic processes on thin foils in subsonic flow, Dynamics of continuous media with free boundaries. Cheboksary 1996:92–6.
[310] Ellsworth WE, editor. Modern ships and craft, Chap. VI: E.A. Butler, appendix, wing-in-ground effect vehicles. Naval Eng J Special Ed 1985;97:254–8.
[311] Elzebda JM, Mook DT, Nayfeh AH. Numerical simulation of wingships. In: Proceedings of the intersociety high performance marine vehicle, conference and exhibit, HPMV'92, Ritz-Carlton Hotel, Arlington, VA, WS28-WS37, 24–27 June 1992.
[312] Englar RJ, Schuster DM, Ford DA. Evaluation of the aerodynamics and control of unlimited racing hydroplanes operating in and out of ground effect. AIAA 91-0553, 1991.
[313] Er-EL J, Weihs D. Ground effect on slender wings at moderate and high angles of attack. J Aircraft 1986; 23(5):357–8 May.
[314] Eroshin VA. Unsteady motion of a foil near a wavy ground, Izvestia AN SSSR. Mekh Zhidkosti i Gaza 1973(3):10–6.
[315] Ermolenko SD. Nonlinear theory of small aspect ratio wings. Izvestia VUZov, Aviatsionnaya Tekhnika no. 2, 1966.
[316] Ermolenko SD, Rovnykh AV. Contribution to nonlinear wing. Izvestia VUZov, Aviatsionnaya Tekh 1967;10(2).
[317] Ermolenko SD, Khrapovitskiy VD. Influence of air compressibility on the aerodynamic characteristics of a wing moving at subsonic speed near the earth's surface. Izvestia VUZov, Aviatsionnaya Tekh 1969;12(4).
[318] Ermolenko SD, Khrapovitskiy VD. Aerodynamic Characteristics of wing systems moving at subsonic speeds near the earth or smooth water surface, Samolyotostroyenie I Tekhika Vozdushnogo Flota, Kharkov, 1973.
[319] Ermolenko SD, Rogozin Yu A, Rozhin VN. Calculation of nonlinear characteristics of aeroplanes at small speeds. Problemy Aerodynamiki Prostranstvennykh Konfiguratsiy, Trudy ITPM SO AN SSSR, 1982. p. 9–15.
[320] Ershov A. Naval ekranoplan will turn into a rescue vehicle, Izvestia, 4 January 1994.
[321] Fach K, Peterson U. WIG safety-a classification society point of view. In: Proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 12, 4 and 5 December 1997.
[322] Farberov Ya F, Plissov NB. Rotational Derivatives of V-shaped wings near the interface. Trudy NTO Sudproma imeni Akad. A.N. Krylova, vyp.88, 1967. p. 130.
[323] Filipchenko GC, Shadrin VP. Effect of end plates on the lift of a wing moving over the surface of water. Sbornik Statey po Voprosam Gidrodinamiki Grebnykh Vintov I Bystrohodnikh Sudov, 1967.
[324] Filipchenko GG. Ekranoplan KAG-3 and its trials (Ekranoplan KAG-3 i ego Ispytaniya). Katera i Yakhty 1968(5):21–2.
[325] Fischer H. RFB research and development in WIG vehicles. AIAA 89-1495, 1989.
[326] Fischer H, Matjasic K. Some thoughts about the use of lift-off aids as one condition for the economic operation of wig ships. In: Proceedings of the international workshop on ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 60–77.
[327] Fischer H. The Hoverwing technology—bridge between WIG and ACV. In: Proceedings of the EuroAvia ground effect symposium, SUPAERO, Toulouse, France, 12–15 June 2001. p. 45–70.
[328] Flying boats from Tasmania. Work Boat World, vol. 15(1), April 1996.
[329] Fock H. Advanced naval vehicles, Naval Forces, April 1983. p. 74–80.
[330] Forschag WF. Literature search and comprehensive bibliography of wings in ground effect and related phenomena, no. 2179, DTMB report, March 1966.
[331] Fridman GM. Nonlinear Local solutions to free s urface lifting flow problems in extreme ground effect. In: Proceedings of the 2nd international conference asymptotics in mechanics—AiM 96, St. Petersburg: St. Petersburg State Marine Technical University; 1996. p. 89–96.
[332] Fuller GH. Near surface vehicles—the next breakthrough of the Niche Cul-de-Sac?, In: Proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 1, 4 and 5 December 1997.
[333] Furlong GC, Bollech TV. Effect of ground interference on the aerodynamic characteristics of a swept back wing. NACA TN- 2487, 1948.
[334] Fuwa T, Hirata N, Hasegawa J, Hori T. Fundamental study on safety evaluation of wing-in surface effect ship (WISES). In: Proceedings of the 2nd international conference on fast sea transportation—FAST 93, Yokohama, Japan, 13–16 December 1993, p.1585–96.
[335] Fuwa T, Minami Y. A Study on the motion of wing-in-surface effect ships by means of computer simulation. In: Proceedings of the 2nd international conference on ekranoplans, Nizhniy Novgorod, May 1994.
[336] Fuwa T. R&D of wing-in-surface effect ship in Japan. In: Proceedings of KTTC workshop on super-high speed ship, Daejon, Korea, 1994.

[337] Fuwa T, Takanashi N, Hirata N, Kakugawa A. A study on the conceptual design of wing in surface effect ships. In: Proceedings of the 6th international symposium on practical design of ships and mobile units. Seoul, Korea: Society of Naval Architects of Korea; 17–22 September 1995. p. 1.735–46.
[338] Fuwa T. et al. Simulation study of the behavior of wing-in-surface effect ships. FAST 95, no. 1, Lubeck-Travemunde, Germany, 25–27 September 1995. p. 609–20.
[339] Gadetski VM, Pavlovets GA, Rudenko SI. Particular features of the flow past a foil near the ground in the wind tunnel. Trudy TSAGI, vyp. 1233, 1970.
[340] Gadetski VM. The influence of the form of the foil upon its aerodynamic characteristics near the ground. Trudy TSAGI, vyp. 2304, M., 1985. p. 3–12.
[341] Gaines M. USA joins Russia on wingship, Flight International, 11 March 1992. p. 5.
[342] Gallington RW, Miller MK, Smith WN. The ram wing surface effect vehicle: comparison of one dimensional theory with free flight results, Hovering craft and hydrofoil, vol. 11, February 1972, p. 10–9.
[343] Gallington RW. RAM wing surface effect boat. J Hydronaut 1973;7(3):118–23 July.
[344] Gallington RW. Vortex shedding from the ram wing vehicle. In: Paper presented at the international hovering craft, hydrofoil and advanced transit systems conference, Brighton, England, 13–16 May 1974.
[345] Gallington RW, Chaplin HR, Krause FH, Miller JA, Pemberton JC. Recent advances in wing-in-ground-effect vehicle technology. AIAA paper no. 76–874, September 1976.
[346] Gallington RW. Sudden decelleration of a free jet at the entrance to a channel. DTNSRDC report ASED 350, January 1976.
[347] Gallington RW, Chaplin HR. Theory of power augmented ram lift at zero forward speed. DTNSRDC report ASED 365, February 1976.
[348] Gallington RW, Krause FH. Recent advances in wing in ground effect technology. In: AIAA/SNAME advanced marine vehicle conference, Arlington, VA, September 1976
[349] Gallington RW. Approximate forces on hard WIG end plates penetrating waves and limits on yaw angle and speed, DTRDC, TM 16-77-107, January 1977.
[350] Gallington RW. The RAM augmented catamaran. AIAA paper no. 86-2365, September 1986.
[351] Gallington RW. Power augmentation of wing in ground effect craft. In: Proceedings of the intersociety high performance marine vehicle, conference and exhibit, HPMV'92, Ritz-Carlton Hotel, Arlington, VA, WS9-WS16, 24–27 June 1992.
[352] Garay EK. Effect of the ground board boundary layer on air cushion vehicle wind tunnel tests. UTIAS technical note 100, University of Toronto, Institute for Aerospace Studies, January 1967. p. 41 + vi.
[353] Gebert GA, Atassi HM. Unsteady vortical disturbances around a thin foil in the presence of a wall. AIAA J 1989;27:1448–51.
[354] George AR, Donis JE. Flow patterns, pressures and forces on the underside of idealised ground effect vehicles. Am Soc Mech Eng, Fluids Eng Div 1983;7:69–79.
[355] Gera J. Stability and control of wing-in- ground effect vehicles or wingships. AIAA 95-0339, 1995.
[356] Gersten K. Berechnung der Aerodynamischen Beiwerte in Bodennaehe, Abhandlung der Braunschweigischen Wissenschaftlichen Gesellschaft XII, 1960.
[357] Gersten K. Calculation of the aerodynamic characteristics of wings of finite span near the ground. RAE transactions 1054, December 1963.
[358] Goetz AR, Osborn RF, Smith ML. Wing-in-ground effect aerodynamic predictions using PANAIR. In: Paper presented at the AIAA aircraft design systems and operations meeting, AIAA paper 84-2429, 1984.
[359] Golubentsev AN, Akimenko AP, Kirichenko NF. Criterion for autostabilization of the motion of a system of two wings close to a screen. Soviet high-speed hydrodynamics, no. 4, 1968.
[360] Golubev VV. Toward a theory regarding ground effect on the lift of an airfoil. Teoreticheskiy Sbornik TsAGI, no. 301, Moscow, 1937.
[361] Goss H. Is it a boat is it a plane. New Sci 13 April 1996.
[362] Grad P. Ekranoplanes: ground or water skimming craft could fill transport Niche. Eng Aust 1995;67(12) December.
[363] Gratzer LB, Mahal AS. Ground effects in STOL operation. J Aircraft 1972;9:236–42.
[364] Greene WJ. The hoverplane TM advanced wingship design from Wingship Inc. In: Proceedings of the international workshop on ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 295–8.
[365] Greene WJ. Wing-in-surface effect ferries: the imminent future of ultra-fast ferries is off the water. In: Proceedings of the international conference on wing-in-ground effect craft, London, paper no. 9, 4 and 5 December 1997.
[366] Greene WJ. The Hoverplane progress report. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998, p. 241–6.
[367] Grillo C, Gatto C. Dynamic stability of wing-in-ground effect vehicles: a general model. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[368] Grinchenko, V., Moroz, V. Hydrodynamic aspects of wing-in-ground effect designing. In: Proceedings of the 1st international symposium on WIG crafts, Sofitel Ambassador Seoul, Korea, 8 November 2005, p. 15–25.
[369] Grundy IH. Airfoils moving close to a dynamic water surface. J Aust Math Soc B27 1986(3):327–45.
[370] Grunin E. Soaring above the water (Nad Vodoi Paryaschiye. Tekh Molodezhi 1974(12):30–4.
[371] Grunwald KJ. Aerodynamic charactreristics of high fineness ratio vehicle bodies at cross-wind conditions in ground proximity. NASA Langley working paper, LWP-490, 10 October 1967.
[372] Gunston WT. Surface effect Ship, Air-cushion vehicles, June 1964. p. 80–1.
[373] Gunston WT. Dynamic air-cushion vehicle, Air cushion vehicles, June 1964. p. 80–1.
[374] Gunston WT. The encyclopedia of the Russian aircraft 1875–1995. Motorbooks International, 1995.
[375] Gurianov MA. Surface effect components of the aerodynamic characteristics of a vehicle on an air cushion with upthrust by the incoming flow. Izvestia VUZov, Aviatsionnaya Tekhnika, no. 2, 1978.

[376] Gur-Milner SI. The stable method of determination of aerodynamic forces acting upon a rectangular wing near the ground. Trudy Leningradskogo Korablestroitelnogo Instituta 1975;96:31–6.
[377] Ilyin V. Turns around ekranoplans, Izvestia: We-Mi, January 1994. p. 4.
[378] Ilyinsky NB, Potashev AV, Fokin DA. On some approaches to solution of the problem of aerodynamic optimisation of wing sections of ekranoplans, Tezisy Dokladov NTK Problemy Morekhodnykh Kachestv Sudov I Korabelnoi Gidromekhaniki (XXXVIII Krylovskiye Chteniya), Krylov Institute, St. Petersburg, 1997. p. 113.
[379] International Maritime Organization: development of requirements for wing-in-ground (WIG) craft. Report of the correspondence group, DE 40/11/1, London, November 1996.
[380] International Maritime Organization: interim guidelines for wing-in-ground (WIG) craft, MSC/Circ. 1054, 16 December 2002.
[381] Isay WH, Niermann H. Tip vortices above a lifting wing near the water surface. Z Angew Math Mech 1974;54(1): 62–7.
[382] Ivanteeva LG, Konovalov SI, Pavlovets GA. Calculation of aerodynamic characteristics of the foil near the ground for given magnitudes of its geometric parameters. Uchenie Zapiski TSAGI, tom 11, no. 2, 1980.
[383] Handler EH. Practical considerations regarding wing-in-ground effect aircraft. J Hydronaut 1977; 11(2) 35–41, also in Proceedings of the intersociety high performance marine vehicles conference—HMPV'92, September 1976, Arlington, Virginia, p. 9 + i.
[384] Harlow J, Hodgekinson N. Is it a ship? No it's the Caspian Sea Monster, Sunday Times July 1993.
[385] Harry CW. Wind tunnel investigation of ground effect on a rectangular wing of several moderate aspect ratios. NSRDC report 1979, July 1965.
[386] Harry CW. Wind tunnel investigation of ground effect on a rectangular wing of several moderate aspect ratios. Bureau of Naval Weapons report no. 1979 (Aero report 1086), 1965.
[387] Harry CW, Trobaugh LA. Wind tunnel investigation of an aspect ratio 10 tandem wing configuration in ground effect. Part I—longitudinal characteristics. DTMB report 22591, January 1966.
[388] Harry CW, Trobaugh LA. Wind tunnel investigation of an aspect ratio 10 Tandem wing configuration in ground effect, Part II—lateral characteristics. DTMB report 22592, January 1967.
[389] Hashiguchi M, Ohta T, Kuwahara K. Computational study of aerodynamic behavior of a car configuration. AIAA paper 87-1386, 1987.
[390] Hayes DLB. Aerodynamic ground effect craft—a performance study. Batchelor of Engineering thesis. Australia: The University of New South Wales, November 1994. p. 140 + vii.
[391] Heber CE. The power-augmented-ram wing-in-ground effect concept as an airborne amphibious quick reaction force. In: AIAA 6th marine systems conference, paper 81-2077, Seattle, Washington, 14–16 September 1981.
[392] Hikosaka K, Ahmed MR, Kohama Y. Some aerodynamic characteristics of a tandem wing configuration in close ground proximity. In: Proceedings of the international Workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 209–22.
[393] Hirata N. Simulation of viscous flow around two-dimensional power-augmented RAM Wing in ground effect. J Soc Naval Archit Japan 1993; 174: 47–54 (in Japanese).
[394] Hirata N, Kodama Y. Flow computation for three-dimensional wing in ground effect using multi-block technique (Read at the Spring Meeting 17 and 18th May) J Soc Naval Archit Japan 1995; 177: 49–57.
[395] Hirata N. Numerical study on the aerodynamic characteristics of a three-dimensional power augmented ram wing in ground effect. J Soc Naval Archit Japan 1996;179:31–9.
[396] Hirata N, Hino T. Investigation of a three-dimensional power-augmented ram wing in ground effect. In: AIAA paper 97-0822, 35th aerospace sciences meeting and exhibit, 1997.
[397] Hoerner SF, Borst HV. Fluid-Dynamic Lift, Mrs. Liselotte A. Hoerner, Brick Town, P.O. Box 342, NJ 08723, USA. 1979.
[398] Holloway C. Potential commercial viability. In: Proceedings of a workshop on twenty-first century flying ships. Sydney, Australia: The University of New South Wales; 7 and 8 November 1995. p. 148–54.
[399] Holloway C. Development and ComMERCIALISATION OF THE Rada Craft G-35. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New SouthWales; 5–6 December 1996. p. 2–11.
[400] Holloway C. The flight of the Phoenix. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 47–54.
[401] Honert H. Die Technik von Bodeneffektflugzeugen, Institut fuer Flugmechanik, Braunschweig, June 1994.
[402] Hooker SF, Terry MR. Hydroaviation. In: Proceedings of the intersociety high performance marine vehicle, conference and exhibit, HPMV'92, WS1-WS8, 24–27 June, Ritz-Carlton Hotel, Arlington, VA, 1992.
[403] Hooker SF. Twenty century shipping at aircraft speeds. In: Proceedings of the a workshop on twenty-first century flying ships. Sydney, Australia: University of New South Wales; 7 and 8 November, 1995. p. 178–232.
[404] Hooker SF. Some thoughts on the commercialisation of ekranoplans and wingships. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 272–94.
[405] Hori T, Hirata N, Tsukada Y, Fuwa T. A Study of the surface effect phenomena and characteristics of WISES. In: Abstract of the 64th general meeting of Ship Research Institute, December 1994. p. 153–6 (in Japanese).
[406] Hsiun C-M, Chen CK. Numerical calculation and investigation of aerodynamic characteristics of two-dimensional wing in ground effect. In: The 6th national conference of the society of naval architecture and marine engineering. Chiayi, Taiwan, ROC: Society of Naval Architecture and Marine Engineering of the Republic of China; 1993. p. 1–12.
[407] Hsiun C-M, Chen C-K. Aerodynamic characteristics of a two-dimensional airfoil with ground effect. J Aircraft 1996;33(2):386–92.

[408] Hsiun C-M, Chen CK. Improved procedure for the inverse design of two-dimensional airfoils in ground effect. J Aircraft 1996;33(6).
[409] Huffman JK, Jackson CM. Investigation of the static lift capability of a low aspect ratio wing operating in a powered ground effect mode. National Aeronautics and Space Administration TM X-3031, July 1974.
[410] Hu An-Ding, On the aerodynamic characteristics of thicker wings in ground effect with end plates. Shipbuilding of China, no. 71, 1989 (in Chinese).
[411] Hu An-Ding. Aerodynamic characteristics of amphibian wing-in-ground effect craft. Recent Adv Wind Eng 1989;2:1130–9.
[412] Hummel D. Nichtlineare Tragfluegeltheorie in Bodennaehe. Z Flugwissensch 1973;21(12):425–42.
[413] Hutchinson JL. Further measurements of ground interference on the lift of a southampton flying boat. ARC R&M 1747, 1936. p. 811–5.
[414] Hynds P. WIG deployment becomes commercial reality, Speed at Sea, Riviera Maritime Media Ltd., August 2002, p. 16–18.
[415] Jackes AM. Development of the axial flow surface effect vehicle. AIAA paper no. 72–602, July 1972.
[416] Jacob K. Advanced method for computing flow around wings with rear separation and ground effect. J Aircraft 1987;24(2):26–128.
[417] Jane's Defence Weekly, 21 July 1984. p. 59.
[418] Jane' s all the world's surface skimmers, 1995–1996.
[419] Jeong SM, et al. Numerical calculation of flow fields around a 2D WIG. In: 95th fall meeting of the Society of Naval Architecture of Korea, 1996 (in Korean).
[420] Kaario TJ. Translation from Finnish of two patents and one paper describing T.J. Kaario's early work on air cushion vehicles (1932–1949). Report no. AR-595, Aerophysics Company, Washington, DC, 6 November 1959.
[421] Kaiser SA. The legal status of ekranoplanes, Aero. Space LAW, vol. XVII, 1993.
[422] Kataoka K, Ando S, Nakatake K. Free surface effect on characteristics of 2D wing. Trans West Jpn Soc Nav Archit 1991; 83: 21–30 (in Japanese).
[423] Katz J. Calculation of aerodynamic forces on automotive lifting surfaces. J Fluids Eng 1985;107:438–43.
[424] Katzoff S, Sweberg HH. Ground effect on downwash angles and wake location, NACA report 738, 1942. p. 12.
[425] Kawamura T, Kubo S. Numerical simulation of wing in ground effect. Special publication of National Aerospace Laboratory, SP-9, November 1988, p. 223–7 (in Japanese).
[426] Kawamura T, Kubo S. Numerical simulation of wing in ground effect. In: A collection of technical papers international symposium of computational fluid dynamics, Nagoya, 1989. p. 1037–42.
[427] Kawamura T, Kubo S. Three-dimensional Navier–Stokes computation of the flow around the wing-in-surface-effect craft. In: Paper presented at the 2nd international conference on 2ekranoplans, Nizhniy Novgorod, May 1994. p. 9.
[428] Kehoe JW, Brower KS. Wing-in-ground-effect vehicles. Naval Eng J, Am Soc Naval Eng February 1985.
[429] Kemp WB, Lockwood VE, Phillips WP. Ground effects related to landing of airplanes with low aspect ratio wings. NASA TND-3583, 1966.
[430] Kida T, Miyai Y. Jet-flapped wings in very close proximity to the ground. AIAA J 1973;10(5):611–6.
[431] Kida T, Miyai Y. Minimum induced drag of nonplanar ground effect wings with small tip clearance. Aeronaut Q 1974;XXV:19–36.
[432] Kida T, Miyai Y. A theoretical note on the lift distribution of a nonplanar ground effect wings with small tip clearance. Aeronaut Q 1974;XXV:19–36.
[433] Kida T, Miyai Y. An alternative analytical method for ground effect airfoils. Aeronaut Q 1976;27:292–303.
[434] Kidwell GH, Gallington RW. Effect of configuration on the measured performance of a power augmented wing-in-ground effect. DTNSRDC ASED-380, 1977.
[435] Kim SK, et al. A fundamental study of WIG craft. In: Proceedings of the workshop on high-speed ships. Korea: KRISO, Daejon; 1995.
[436] Kim, S-K, Shin YK, Kim JH. Development and status of WISES (wing-in-surface- effect ship). In: Proceedings of the workshop on WIG ship technology. Yusung, Korea: Korea Research Institute on Ships and Ocean Engineering; 1–6 June 1995. p. 1–10.
[437] Kim YG, Jeon JY, Jang HS. Optimization of 3-D wing in surface effect using the surface panel method. In: Proceedings of the Society of Naval Arhitects of Korea, Spring Meeting, May 1995.
[438] Kim SK, Suh SB. Wind tunnel test study on wings of WIG ship. In: Proceedings of the 3rd Korea–Japan joint workshop on ship and marine hydrodynamics, Korea, July 1996.
[439] Kim WJ, Shin MS. Numerical calculation of the flow around a wing in surface effect. In: Proceedings of the 3rd Korea–Japan joint workshop on ship and marine hydrodynamics, Korea, July 1996.
[440] Kirillovykh V, Kuznetsov G. On definition of some aerohydrodynamic configuration of the Spasatel Russian search-and-rescue ekranoplan. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 102–13.
[441] Kobayakawa M, Maeda H. Gust response of a wing near the ground through the lifting surface theory. J. Aircraft 1978; 15: 520–5.
[442] Kocivar B. Ram-wing X-114 floats, skims and flies. Popular Sci 1977;211:70–3.
[443] Kono T, Kohama Y. Stability of guide-way type WIG vehicle. In: Proceedings of the 3rd JSME-KSME fluids engineering conference, 1994. p. 715–8.
[444] Konov EA. Steady hydroaerodynamic characteristics of wings in motion with yaw and heel near the interface of two media. Sbornik NTO Sudproma imeni akad. A.N. Krylova, Leningrad, Sudostroenie, vyp. 143, 1970. p. 89–97.
[445] Konov EA. Positional and rotational characteristics of sweeped wings of arbitrary planform and lateral cross-section in threedimensional motion near the air–water interface. Sbornik NTO Sudproma imeni akad. A.N. Krylova, Leningrad, Sudostroenie, vyp. 168, 1971. p. 275–86.
[446] Kornev NV, Treshkov VK. Numerical investigation of nonlinear unsteady aerodynamics of the WIG vehicle. In: Proceedings of the intersociety high performance marine vehicles conference and exhibit HMPV 92, VA, 24–27 June 1992. p. WS 38–48.

[447] Kornev NV. Survey of software developments of the center of mathematical modelling of Marine Technical University in the field of aerodynamics and dynamics of ekranoplans. In: Proceedings of the 1st international conference on ekranoplans. St. Petersburg: Marine Technical University; 3–5 May 1993. p. 73–5.
[448] Kornev N, Kudryavtsev A, Zakharov A. WIGSIM: wing-in-ground effect vehicle flight simulator. In: Proceedings of the 2nd international conference on fast sea transportation—FAST 93, Yokohama, Japan, 13–16 December 1993. p. 1555–60.
[449] Kornev NV. Mathematical model of the ekranoplan aerodynamics. In: Proceedings of the workshop on WIG ship technology. Yusung, Korea: Korea Research Institute on Ships and Ocean Engineering; 1–6 June 1995. p. 12.
[450] Kornev NV, Reichert G. Vortex decay of ekranoplan. In: Proceedings of the German aerospace congress, DGLR—Jahrbuch, Dresden 1996;2:1043–52.
[451] Kornev NK, Reichert G. Three-dimensional instability of a pair of trailing vortices near the ground. AIAA J 1997;35(10):1667–9.
[452] Kornev NV, Treshkov VK, Reichert G. Dynamics of trailing vortices near the ground, IUTAM symposium on dynamics of vortices, 31 August–8 September. Aachen, Germany: Kluwer Academic Publishers; 1997.
[453] Kornev NV, Treshkov VK. Dynamics of trailing vortices of ekranoplans. Tezisy Dokladov NTK Problemy Morekhodnykh Kachestv Sudov i Korabelnoi Gidromekhaniki (XXXVIII Krylovskiye Chteniya), Krylov Institute, St. Petersburg, p. 111–2.
[454] Kornev NV, Taranov AE, Treshkov VK. Efficient software for numerical calculation of ekranoplans (WIG Crafts) and hydrofoils. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 263–6.
[455] Kornev NV, Matveev K. Complex numerical modeling of dynamics and crashes of wing-in-ground vehicles. AIAA paper 2003-600, 41st aerospace sciences meeting and exhibit, 6–9 January 2003, Reno, Nevada, 2003. p. 9.
[456] Korolev VI. Longitudinal static stability of vehicles with two lifting wings. Gidrodinamika Nesuschukh Poverkhnostei, Moscow, 1966.
[457] Korolev VI. Motion of a Vehicle with lifting aerofoils over a rippled water surface. Gidrodinamika Bolshikh Skorostei, no. 2, 1966.
[458] Korolev VI. Longitudinal stability of ekranoplans and hydrofoil ships. In: Proceedings of the symposium on fluid dynamics problems of vehicles operating near or in the air–sea interface. Amsterdam, The Netherlands: Research and Technology Organization; 5–8 October 1998.
[459] Kostin AG. Investigation of motion of a lifting system near the ground. Trudy Irkutskogo Polytekhicheskogo Instituta, vyp. 52, 1969. p. 225–32.
[460] Kostychev GI. On potential flow past a foil near a flat ground. Trudy Kazanskogo Aviatsionnogo Instituta, 1955.
[461] Krause FH. Parametric investigation of a power augmented ram wing over water. ASED TM 16-76-95, 1976.
[462] Krause FH. Evaluation of a power augmented ram wing operating free in heave and pitch over water. DTNSRDC ASED 385, August 1977.
[463] Krause FH, Gallington RW. Static performance of a power augmented ram wing. DTNSRDC ASED-382, 1977.
[464] Krause FH, Gallington RW, Rousseau DG. The current level of power-augmented-RAM wing technology. AIAA paper no. 78-752, April 1978.
[465] Kubo S. A production model of WIG as a high speed marine craft: 'Marine Slider μ-Sky 2', FAST 91, Trondheim, Norway, 1991. p. 607–22.
[466] Kubo S. A concept of wing-in-surface-effect craft as a future passenger transport in Japan, FAST 93, Yokohama, Japan, 1993. p. 1573–84.
[467] Kubo S. Some aspects of development of ekranoplans. In: Proceedings of the 1st international conference on ekranoplans. St. Petersburg: Marine Technical University, 3–5 May 1993. p. 76–9.
[468] Kubo S. Russian ekranoplans. J Jpn Soc Aero/Space Sci 1996;44(505):63–70.
[469] Kubo S, Rozhdestvensky KV. An outline of conceptual design and feasibility analysis of a flying wing configuration on the basis of extreme ground effect theory. In: A paper presented at the FAST 97. Sydney, Australia: The University of New South Wales; 21–23 July 1997.
[470] Kubo S, Akimoto H, Ohtsubo K, Batkhurel G, Manabe K. A new field of wing-insurface effect craft. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[471] Kubo S, Akimoto H. Wing-in-surface effect ship and further development of Asian countries. In: Proceedings of the 1st international symposium on WIG crafts, Sofitel Ambassador Seoul, Korea, 8 November 2005, p. 47–53.
[472] Kühmstedt T, Milbradt G. Aerodynamic design of wing in ground effect craft. FAST 95, Lubeck—Travemunde, vol. 1, Germany, 25–27 September 1995. p. 597–608.
[473] Kühmstedt T. Aerodynamic design procedure and results of the development of commercial WIG craft. In: Proceedings of the international workshop on ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 20–37.
[474] Kumar PE. On the longitudinal stability of a ground effect wing. College of aeronautics report, Aero 202, 1968.
[475] Kumar PE. On the lateral stability of a ground effect wing. College of Aeronautics report, Aero 207, 1968.
[476] Kumar PE. An analogue simulation of the longitudinal motion of a ground effect wing. College of aeronautics report, Aero 208, 1968.
[477] Kumar PE. On the stability of the ground effect wing vehicle. PhD thesis, Southhampton University, June 1969.
[478] Kumar PE. Some stability problems of ground effect vehicles in forward motion. Aeronaut Q 1972;XVIII:41–52.
[479] Kuznetsov A. Caspian Monster Tekhnika Molodezhi, 1992. p. 1–3.
[480] Kystiakovsky AV. Flight in ground effect. In: Proceedings of the 4th all–Russia conference on bionics, 1973. p. 51.
[481] Laitone EV. Comment on drag reduction factor due to ground effect. AIAA J Aircraft 1989;27(1):96.
[482] Lan ZF. Structure of the wing-in- ground-effect vehicle and its development. In: Proceedings of China international boat show and high performance marine vehicles (HPMV) conference, 2003. E14.
[483] Lane WH, Wells WR. Stability design criteria for surface effect aircraft. AFFDL/FGC-TM-76-5, Wright-Patterson AFB, 1977.
[484] Lange RH, Moore JW. Large wing-in-ground effect transport aircraft. J Aircraft 1980;17(4):260–6.

[485] Lenorovitz JM. Russians completing new ground effect vehicle. Aviat Week Space Technol. 26 April 1993; 62–3.

[486] Leslie J. The commercialisation of sea wing ground effect vehicles. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 12–9.

[487] Le Sueur M. Ground effect on take-off and landing of airplanes. TM no. 4, NACA, 1935.

[488] Liang Y, Quan SY. Development of air cushion vehicles in china in the last three decades. In: The international high performance vehicle conference, November 1988, p. 1–24.

[489] Licher RM. Increase in lift for two- and three dimensional wings near the ground. Douglas report no. SM-22615, Santa Monica Division, 1959.

[490] Lifenko AP, Rozhdestvensky KV. Calculation of critical speeds of loss of stability of an elastic wing in the incompressible flow in extreme proximity to the ground. Gidrodinamika Ogranichennykh Potokov, Shuvashskiy Universitet, Cheboksary, 1988. p. 76–85.

[491] Lifenko AP, Rozhdestvensky KV. Calculation of critical speeds of static and dynamic stability of an elastic wing in very close proximity to the ground. Trudy Leningradskogo Korablestroitelnogo Instituta, Matematicheskoe Modelirovanie in Systemakh Avtimatizirovannogo Proektirovania, 1989. p. 28–37.

[492] Lifenko AP, Rozhdestvensky KV. Forced oscillations of an elastic wing in the flow of incompressible fluid at vanishingly small ground clearances. Trudy NTO Im. Akad. A.N. Krylova, Materialy po obmenu opytom, vyp. 495, Sovershenstvovanie khodovykh, morekhodnykh i manevrennykh kachestv sudov, 1989. p. 60–71.

[493] Liiva J. A facility for dynamic testing of models of airborne vehicles with ground effect, UTIA TN-53, October 1963.

[494] Lipovoi GS. Flow past a plate situated near a solid ground plane. Gidrodinamika Bolshikh Skorostei, no. 1, 1965.

[495] Lippisch AM. Tow tank tests of a low aspect ratio ground effect surface. Collins radio engineering report (CER), 1117-8, 1963.

[496] Lippisch AM. The aerodynamic ground effect and the development of the aerofoil boat. Luftfahrtechnik-Raumfahrtechnik 1964;10:261–9.

[497] Lissaman PB. A linear theory for the jet flap in ground effect. J Aircraft 1967;4(6):555–6.

[498] Lissaman PBS, Schollenberger CA. Analysis of thick, cambered jet flap airfoils in ground effect. AIAA Paper 1969;0(738) p. 6, ill.

[499] Ming LS, Kaixie L. The 902 single-seat ram wing surface effect craft. In: International high-performance vehicles conference, Shanhai, China, 1988.

[500] Lockheed California Company. Wind tunnel investigations of single and tandem low aspect ratio wings in ground effect. Lockheed fluid dynamics laboratory report L-53, May 1963, or US Army Transportation Research Command, Fort Eustis, Virginia, TRECOM technical report 63-63, March 1964 or LR 16096; May 1963, SD 600498.

[501] Lohr R. Der Stahlklappenfluegel in Bodennaehe unter besonderer Beruecksichtigung grosser Anstell und Strahlklappenwinkel, Bochum, 1973.

[502] Lotov AB. On forces, acting on a vortex, moving above a free water surface. Tekhn. Otchety TSAGI, vyp. 237, 1963. p. 3–16.

[503] Lukaschik EP. Motion of a wing over a wavy boundary at an arbitrary angle to the wave front. Trudy Chuvashskogo Universiteta, Dynamika Sploshnykh Sred S Granitsami Razdela, Cheboksary, 1983. p. 83–7.

[504] Lukaschik EP. Some nonlinear effects due to a wing motion above wavy boundary, Dinamika sploshnoi sredy s nestatsionarnymi granitsami, Cheboksary, 1984. p. 72–9.

[505] Lukashenko AN, Laptev YuI, Novikov AG. Effect of the planform on the aerodynamic characteristics of a wing close to an underlying surface. Gidrodinamika Bolshikh Skorostei, no. 4, Kiev, 1974.

[506] MacCabe EF. Parametric investigation of a power augmented ram wing with load alleviation devices over irregular waves. DTNSRDC ASED TM 16-76-97, 1976.

[507] MacCabe EF. Assesment of load alleviation devices installed on a power augmented RAM wing over irregular waves. DTNSRDC ASED-383, August 1977.

[508] McGourty C. Soviet Air Monster goes west, Independent, June 1992.

[509] Malyshev MI. Experience of using ekranoplans in Russian navy. In: Proceedings of the international workshop on twenty-first century flying ships. Sydney, Australia: University of New South Wales; 7–9 November 1995. p. 233–44.

[510] Malthan LV. Scaling considerations for the model testing of power augmented ram vehicles. In: Presentation at wing-in-ground effect technology workshop, WPAFB, 1978.

[511] Mamada H, Ando S. Minimum induced drag of a semicircular ground effect wing. J Aircraft 1973;10:660–3.

[512] Mamada H, Ando S. Minimum induced drag of a semielliptic ground effect wing. J Aircraft 1974;11:257–8.

[513] Manor Y. Wingfoil interface craft concept. In: Paper presented at the 6th international conference on high speed surface craft, 1988. p. 295–302.

[514] Martin CJ, Krause FH. The design impact of power augmented ram technology on large energy efficient aircraft. In: The presentation at the AIAA aircraft systems and technology meeting, AIAA paper 79-1864, NY, New York, 20–22 August 1979.

[515] Maskalik AI, Treschevsky VN. Wingship compendium, Forma Corporation.

[516] Maskalik, A.I., (1993) Main results of developments in the field of aerodynamics and flight dynamics of ekranoplans. In: Proceedings of the 1st international conference on ekranoplans. St. Petersburg: Marine Technical University, 3–5 May 1992. p. 12–22.

[517] Maskalik AI. Transport ekranoplans are designed. In: Proceedings of the 2nd international conference on ekranoplans, Russia, Nizhniy Novgorod, 1994.

[518] Maskalik AI. The Main problems to be solved during design of ekranoplans of the second generation. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 200–8.

[519] Maskalik AI, et al. Ekranoplans—transport ships of the XXI century. St. Petersburg: Sudostroenie Publishers; 2005. p. 576.

[520] Maskalik AI. Problematic questions of aerohydrodynamics and dynamics of motion of transport ekranoplans. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.

[521] Maskew B. On the influence of camber and non planar vortex wake on wing characteristics in ground effect. In: Aeronautics Research Council, Aeronautical research council papers, CP no. 1264, 1973.
[522] Masuda S, Suzuki K. Simulation of hydrodynamic effects of 2-dimensional WIG moving near the free surface. J Soc Naval Archit Jpn 1991; 170: 83–92.
[523] Matsubara T, Higashia A, Matsuoko T, Yamaguchi N, Uragami K. Development of wing in ground effect craft—Marine Slider for high speed boating and pleasure. Mitsubishi Tech Rev August 1991; 137–42.
[524] Matsubara T, et al. Lift enhancement of ground effect wing (1st report). Results of screening tests of various concepts. Trans Jpn Soc Mech Eng 1992;58(552):2456–63; 2nd report, 1992;58(552):2464–71.
[525] Matsuoka T, Higashida A, Matsubara T, Yamaguchi N, Kubo S. Six-component measurements of a model of a wing-in-ground effect craft marine slider in a low speed wind tunnel. J Jpn Soc Aeronaut Space Sci 1991;39(449): 314–21.
[526] Mayer L. Navigation and safe operation of very fast craft. The need for a safety case? In: Proceedings of the international workshop on ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 194–212.
[527] McAfee DR, Walker RL. Structural weight estimate of a wing-in-ground effect vehicle. Programs Department technical memorandum CRDKNSWC/TM-22-93/96, March 1993.
[528] McDaniel M, Snyder C. Airborne amphibians are here again. In: Naval proceedings, October 1993. p. 86–9.
[529] McLeavy R, editor. Jane's surface skimmers, 9th ed. Passim (reference to KAG-3, RAM 1, and RAM 2), 1967–1968.
[530] McLeavy R, editor. Jane's surface skimmers, hovercraft and hydrofoils. 11th ed. London: Samson Low, Marston & Co. Ltd.; 1978 (reference to Hennebutte, X-114, ESKA, Seaglide, and Lockheed).
[531] McLeavy R., editor. Jane's surface skimmers, 7th ed. (reference to Hennebutte), 1973–1974.
[532] McLeavy R. Soviet navy develops WIG SS-N-22 missile craft. Jane's Defence Weekly, 21 July 1984. p. 59.
[533] McMasters J, Greer RA. Conceptual study for a new winged surface effect vehicle system. Naval Eng J, IV 1974;86:41.
[534] Mellow C. When ships have wings, Air and Space/Smithsonian, December 1995/January 1996. p. 52–9.
[535] Menshikov VI. Thin airfoil with high-lift devices near a screen. Samolyotostroeniye I Tekhnika Vozdushnogo Flota, no. 34, Kharkov, 1974.
[536] Meyer E. Hat das Wingship eine Zukunft, Hansa, vol. 130(9), September 1993. p. 31–6.
[537] Meyer M, Ebert J. Investigations on wing-in-ground effect craft using lift-off aid. In: Proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 18, 4 and 5 December 1997.
[538] Mikhailova LV, Shumski GM. Unsteady aerodynamic characteristics of a foil in separated motion near wavy wall. Izv SO AN SSSR, Ser Tekh 1985;0(4/1):56–60.
[539] Minami K, Nakatani H, Miyai Y. Two-dimensional ram wing in parallel walls. Trans Jpn Soc Aero Space Sci 1974;17(35):10–26.
[540] Mizutani N, Suzuki K. Numerical analysis of 3-D WIG advancing over still water surface. J Soc Naval Archit Jpn 1993;174:35–46 (in Japanese).
[541] Mitsubishi develops high speed gliding boat. Sea Technol September 1990; 111.
[542] Modern ships and craft. Appendix: wing-in-ground effect vehicles. Naval Eng J February 1985.
[543] Mook DT, Nuhait AO. Simulation of the interaction between aerodynamics and vehicle dynamics in general unsteady ground effect. In: Intersociety advanced marine vehicles conference, Arlington, VA, Also AAA paper 89-1497-CP; 5–7 June 1989. p. 430–45.
[544] Moore JW. Conceptual design study of powered augmented ram wing-in-ground effect aircraft. In: Presented as paper 78-1466 at the AIAA aircraft systems and technology conference, 21–23 August 1978.
[545] Morishita E, Tezuka K. Ground effect calculation of two-dimensional airfoil. Trans Jpn Soc Aero Space Sci 1994;36(114):270–80.
[546] Morrocco JD. Soviet ground effect aircraft revealed. 7 October 1991. p. 26.
[547] Murao R, Hanashima T, Hori T. On the momentum model for PAR-WIG. In: Aircraft symposium, Hiroshima, 1995 (in Japanese).
[548] Murao R, Hori T, Tsukada T. A study of a WIG with upper surface blowing (USB) PAR. In: Proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 4, 4 and 5 December 1997.
[549] Nagahara, T. Study of the wing in surface effect ship. Master thesis, Aoyama-Gakuin University, 1993 (in Japanese).
[550] Nagamatsu T, Hoshino T, Kure F, Iizuka T, Miyoshi A, Matsubara T. Study of aerodynamic chracteristics of wing in ground effect. J Kansai Soc Naval Arhit, Japan 1992;218:145–52 (in Japanese).
[551] Nagapetyan RA, Synitsin DN. Current status and future trends of transport groundeffect machines (ekranoplans). In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[552] Nangia RK. Aerodynamic and hydrodynamic aspects of high speed water surface craft. Aeronaut J 1987; 91.
[553] Nebylov A, Tomita N. Ekranoplan designing experience revision in view of its use for aerospace plane assist at launch and landing. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 191–9.
[554] Nebylov AV, Zhigalko ET. Aerodynamic scheme of ekranoplane optimization with reference to new areas of application. In: Proceedings of the symposium on fluid dynamics problems of vehicles operating near or in the air–sea interface. Amsterdam, The Netherlands: Research and Technology Organization; 5–8 October 1998.
[555] Nebylov AV, Tomita N. Optimization of motion control at landing of aerospace plane on ekranoplane. In: 36th AIAA aerospace sciences meeting and exhibition, Reno, AIAA 98-0305, 1998.
[556] Nebylov AV, Wilson P. Ekranoplane—controlled flight close to surface, monograph, Southampton, UK: Wit Press; 2002. p. 226.

[557] Nebylov AV, Tomita N. Project of ekranoplane application for spaceplane assist at horizontal launch and landing. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[558] Nitta K, Ando S. Analysis of a 2-D airfoil motion in proximity to a wavy wall surface—finite difference method. J Jpn Soc Aero Space Sci 1991;451(39):8.
[559] Nitta K, Ando S, Waku H. Finite difference numerical prediction of aerodynamics of airfoil flying over wavy wall. J Jpn Soc Aeronaut Space Sci 1991;39(452):491–5.
[560] Nuhait AO, Mook DT. Numerical simulation of wings in steady and unsteady ground effect. In: AIAA proceedings of the paper, 88-2546-CP, 1988.
[561] Nuhait AO, Mook DT. Numerical simulation of wings in steady and unsteady ground effect. J Aircraft 1989;26: 1081–9.
[562] Nuhait AO, Zedan MF. Numerical simulation of unsteady flow induced by a flat plate moving near the ground. J Aircraft 1993;30(5):661–7.
[563] Nuttall N. Seaplane will cross channel in ten minutes. Times, June 1992.
[564] Ollila RG. Historical review of WIG vehicles. J Hydronaut 1980;14(3):65–76.
[565] On the border between gliding and flight (editor's conversation with A. Kipin). Katera I Jakhty 2: 1989 (in Russian).
[566] Osborn RF, Gallaway CR. In: Wing-in-ground effect technology workshop proceedings. AFWAL/FIMM, September 1978.
[567] Owen PR, Hogg H. Ground effect on downwash with slipstream. ARC R&M 2449, 1952.
[568] Pai PF, Nayfeh AH, Mook DT. Modelling of smart structures for wingships. In: HMPV 92, intersociety high performance marine vehicle conference and exhibit, Arlington, VA, 24–27 June 1992. p. WS49–59.
[569] Painter FC. Soviet surface effect vehicles may challenge western forces. Defense Electron June 1987; 133–48.
[570] Panchenkov AN. Hydromechanics of a hydrofoil. Naukova Dumka, Kiev, 1965.
[571] Panchenkov AN. Problem of the unsteady motion of a wing at variable distances from the ground plane surface. Gidrodinamika Bolshikh Skorostei, no. 2, 1966.
[572] Panchenkov AN. Basics of quadrupole theory of the wing near a solid wall. Asimptoticheskie Metody v Teorii Sistem, Irkutsk, Vyp. 7, 1974. p. 68–97.
[573] Panchenkov AN. Further development of quadrupole theory. In: Asymptoticheskiye Metody v Teorii Sistem, Izdatelstvo Irkutskogo Gosudarstvennogo Universiteta, Irkutsk,vyp. 8, 1975. p. 23–40.
[574] Panchenkov AN. Theory of acceleration potential. Nauka, Novosibirsk, 1975.
[575] Panchenkov AN, Borisuk MN, Yanchevskii AM. Optimal wing with constant seaworthiness, Asymptoticheskie metody v mekhanike, Irkutsk, Sibirskiy Energeticheskiy Institut, 1979.
[576] Papadales BS. An evaluation of a two-dimensional power augmented wing-in- ground effect model under static and dynamic free stream conditions. DTNSRDC ASED-353, 1976.
[577] Papadales BS. The performance of a conceptual multimission power augmented-ram wing-in-ground effect vehicle. David Taylor Naval Ship Research and Development Center ASED-385, 1977.
[578] Parametric and conceptual design study of aircraft wing-in-ground effect (WIG) vehicles. Lockheed Georgia Co., Report no. 76020-30, May 1977 (ANVCE).
[579] Paravyan EA. Profile drag of a wing moving near a supporting surface with partial observance of boundary conditions. Gidrodinamika Nesuschukh Poverkhnostey, Moscow, 1966.
[580] Park IR, Chun HH. A study on the free surface effects on 2-D airfoils. In: Proceedings of the 95 spring meeting of the Korea Committee for Ocean Resources and Engineering. J Ships Ocean Eng 1995;10(1) to appear.
[581] Park IR, Chun HH. Numerical simulation of unsteady performance for 2-D surface effect airfoils. Proceedings of the 95 spring meeting of Korea Committee for Ocean Resources and Engineering, November 1995;10(1).
[582] Park JC, et al. Three-dimensional flow simulations around a wing-in-ground effect ship having complex geometry. In: Proceedings of the 3rd Korea–Japan joint workshop on ship and marine hydrodynamics, Korea, July 1996.
[583] Park J-C, Shin M-S. Numerical computations of flow characteristics around a numerical model of wing-in-ground effect ship having three-dimensional geometry. In: 96th spring meeting of the Korean Committee for Ocean Resources and Engineering, 1996 (in Korean).
[584] Paulson JW, Kjelgaard SO. An experimental and theoretical investigation of thick wings at various sweep angles in and out of ground effect. NASA TP-2068, 1982.
[585] Pavlovets GA. Aerodynamic characteristics of a thin foil near the ground in the flow of ideal incompressible fluid.Trudy TSAGI,vyp. 1011, 1966.
[586] Pavlovets GA. Flow past a foil moving near a wavy wall. Trudy NTO Sudproma imeni akad. A.N. Krylova, vyp. 124, 1969.
[587] Pike D. A true flying boat. Work and patrol boat world, April 1985. p. 25.
[588] Pike D. Flying catamaran gets off the ground. The Sunday Times March 3 1996.
[589] Pipko D. Ekranoplans are winged ships of the future. Nauka i Zhizn 1966(1):33–41.
[590] Pirogov NN, Skorov SA, Samonenko SS, Chernyavets VV. On marine passenger ekranoplans. Sudostroenie 1994(5-6):3–4.
[591] Plissov NB. Motion of a heeled wing above a solid ground. Trudy NTO Sudproma imeni akad. A.N. Krylova, vyp. 104. 1968. p. 83–6.
[592] Plissov NB, Latypov FF. Research of the aerodynamic characteristics of a v-shaped wing in close proximity to a solid surface. Trudy Leningradskogo orablestroitelnogo Instituta, no. 80, 1972.
[593] Plotkin A. Thin ellipse in ground effect: lift without circulation. J Appl Mech, Trans ASME 1988;55(3): 735–6.
[594] Pistolesi E. Il Problema dell'alla in Vicinanza del Suolo. L'Aerotekhnika 1933;13(4).
[595] Pistolesi E. Temi ed Esperienze sul Problema dell' alla in Vicinanza del Suolo,Pubblicazioni della R. Scuola d' Ingegrieria di Pisa, VI, no. 261, July 1935.
[596] Pistolesi E. Ground effect—theory and practice. NACA TM 828, 1937.

[597] Point design for WIG-S, vol. IV—structural analysis. Douglas aircraft report MDC J7406-4, March 1977 (ANVCE).
[598] Pollock L. Skimmer plane takes off on waves of success. New Sci, June 1992.
[599] Ponomarev AV, Ryabtsev YuN, Tanichev BG. New design schemes of of the craft with dynamic support. Sudostroenie za rubezhom, L 1972;0(8):55.
[600] Preliminary economic analysis of winged hull vehicles. Lockheed California Company, Report LA/ME2148, September 1962.
[601] Privalov EI, Kirillovykh VN. Transport amphibious platforms: a new type of high-speed craft. In: Proceedings of the international workshop ekranoplan and very fast craft. The University of New South Wales, 5–6 December 1996. p. 121–33.
[602] In: Proceedings of the 1st international symposium on WIG crafts. Korea: Sofitel Ambassador Seoul, 8 November 2005. p. 84.
[603] Pustoshniy AV, Russetskiy AA. Naval and commercial fast ship development experience and further projects. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[604] Putilin SI. Low-aspect-ratio wing flying above an interface between fluids of different densities. Gidrodinamika Bolshikh Skorostey, 1962.
[605] Quirk P. From concept to commercial reality. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 1–4.
[606] Ram-wing vehicles as water-borne transport facilities, hovering craft and hydrofoils, vol. 14(2), November 1974. p. 11–7 (Original Source: Budownictiwo Okretowe, no. 3, 1974)
[607] Ramsden JM. Bigger and faster. Air-cushion vehicles, November 1966. p. 25–6.
[608] Ram-Wing X-114 Floats, skims and flies. Popular Sci. December 1977; 70–3.
[609] Rattenbury N. Classification of engineering systems for wing-in-ground effect craft. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.
[610] Raymond AE. Ground influence on airfoils. NACA-TN-67, 1921. p. 17.
[611] Rawdon BK, Hoisington ZC. Characteristics of an ultra-large, land-based wing- in-ground effect aircraft. In: Proceedings of the PACIFIC 2004 international maritime conference, vol. 1, session 9-WIGs, 2004. p. 228–36.
[612] Read GM. Extreme ground effect. PhD thesis, University of Adelaide, 1989.
[613] Recant IG. Wind-tunnel investigation of ground effect on wings with flaps. NACA-TN-705, 1939. p. 26.
[614] Reeves JMS, Findley DP. Systems costing of hovercraft, hydrofoil ships and wing-in-ground effect machines. In: Paper for the 15th annual DoD cost analysis symposium, published by J. Watson Noah Inc., October 1980.
[615] Reeves JML. Ram wings—a future? In: Proceedings of the symposium ram wing and ground effect craft. London: The Royal Aeronautical Society, 19 May 1987. p. 7–56.
[616] Reeves JML. Wingship drag prediction. Naval Air Warfare Center, Aircraft Division, Warminster, PA, Prepared for ARPAWTET 5 August 1993.
[617] Reid EG. A full scale investigation of ground effect. TR no. 265, NACA, 1928. p. 7.
[618] Reif TH. A wind tunnel study of the aerodynamics of a tunnel boat hullwith consideration of the ground effect. High-speed surface craft, March/April 1985. p. 29–33.
[619] Rethorst S. The 100-knot 'Columbia', air-cushion vehicles. October 1962. p. 66–73.
[620] Ritchie MD. The research and development methods of Wilber and Orville Wright. Astronaut Aeronaut 1978;16: 56–67.
[621] Roberts P. Ventures hope for plane sailing. Aust Fin Rev, 28 March 1996.
[622] Rousseau DG, Gallington RW. Performance prediction method for a wing in-ground effect vehicle with under-the-wing blowing. DTNSRDC report ASED 379, March 1977.
[623] Rozhdestvensky KV. Ekranoplans—flying ships of the next century. In: Proceedings of the 11th international maritime and shipping symposium Twenty-First Century Shipping. Sydney, Australia: University of New South Wales; 6 November 1995. p. 19 (also in Proceedings of the international workshop ontwenty-first century flying ships. Sydney, Australia: University of New South Wales; 7–9 November 1995. p. 47–70).
[624] Rozhdestvensky KV. Nonlinear aerodynamics of ekranoplan in strong ground effect. FAST 95, vol., 1, Lubeck-Travemunde, Germany, 25–27 September 1995, p. 621–30.
[625] Rozhdestvensky KV. State of the art of Russian Research and development on ekranoplans. In: Proceedings of the workshop on WIG ship technology. Korea Research Institute of Ships and Ocean Engineering, 1–2 June 1995. p. 11–67.
[626] Rozhdestvensky KV, Kubo S. A parametric analysis of a flying wing configuration in extreme ground effect. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 78–96.
[627] Rozhdestvensky KV, Starkov AV. A simple virtual prototyping system for an ekranoplan. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 97–107.
[628] Rozhdestvensky KV, Mikhailov MA. Virtual testing of navigational safety of wing-in-ground effect vehicles. In: Proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 13, 4 and 5 December 1997.
[629] Rozhdestvensky KV, Mikhailov MA. Virtual Navigation, In: Proceedings of the International Workshop WISE up to ekranoplan GEMs, The University of New South Wales, Sydney, Australia, 15–16 June 1998. p. 125–37.
[630] Rozhdestvensky K. A study of a triplan WIG concept based on extreme-ground-effect theory. In: Proceedings of the PACIFIC 2004 international maritime conference, vol. 1. Session 9-WIGs, 2004. p. 255–63.
[631] Rozhdestvensky KV. Wing-in-ground effect vehicles. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), St. Petersburg, Russia, 27–30 June 2005.

[632] Rumiantsev S, Morgachev E. Commercial perspectives of the ekranoplan market. Kommersant-Daily no. 102, 1993.
[633] Russia's mystery monster. Lloyds list, 1 October 1993. p. 9.
[634] Russia: wing-in-ground-effect craft project suffers due to lack of funds. Reuter insurance briefing, 14 February 1994.
[635] Russian shipyards: dramatic changes. Schiff&Hafen/Seewirtschaft no. 9, 1993. p. 27–8.
[636] Sambuy V. di A New Poussiere Navale. Warship, June 1990. p. 1–11.
[637] Saunders D. Aerodynamic characteristics of wings in ground proximity. Can Aeronaut Space J 1965;II June.
[638] Schlichting U.J. Experimentelle und Theoretische Untersuchungen an Tragflugeln und Konfigurationen in Bodenahe. Dissertation, RWTH Aachen, 1985.
[639] Schmitt D. Aerofoil-flugboot Jorg II. Flug Revue, May 1978. p. 70–7.
[640] Schonknecht R, Kloeckner D, Kuehmstedt T, Ebert J. Unkonventionelle Schiffe II: Wirtschaftlicher Wassertransport mit Bodeneffekt-Fahrzeugen. Jahrb Schiffbautechnischen Gesellsch 1994;88.
[641] Schukin EV, Adamyantz AO. Statistical Calculation of aerodynamic coefficients of a wing. Moving Near a Wavy Sea Surface, Trudy MAI, vyp. 282, 1974. p. 46–50.
[642] Scullen D, Tuck E. Free surface elevation due to moving pressure distributions in three dimensions. J Ship Res 2001.
[643] Standingford D, Tuck E. Optimal rectangular endplates. J Aircraft 1996;33(3):623–5.
[644] Schuster S. Vom Flugboot zu den Fluegelbooten, STG Jahrbuch, December 1978. p. 15–26.
[645] Sea Monster from Russia above La Manche, In Zarubezhom, NN 26–27, 1992.
[646] Sears WR. Ground effect with special reference to pitching moments. J Aeronaut Sci 1938;5(5):281–5.
[647] Semenchin VA. Investigation of the form and aerodynamic characteristics of the foil with flexible extensible film close to a solid interface. Aerodinamicheskoye proektirovanie letatelnikh apparatov, Kharkov, 1985. p. 20–30.
[648] Serebriysky YaM. Experimental study of vertical approach to a flat plate and indicial approach of a wing to the ground. Trudy TSAGI imeni N.E. Zhukovskogo, Vyp. 442, Moscow, 1939.
[649] Serebriysky YaM, Biachuev SA. Wind tunnel investigation of the horisontal motion of a wing near the ground. NACA TN-1095, 1946.
[650] Shadrin VP. Aerodynamic Characteristics of a finite-aspect-ratio wing with a flap moving near a solid wall. Gidroaerodinamika Nesuschikh Poverkhnostei, Kiev, Naukaova Dumka, 1966. p. 167–73.
[651] Sheng Q, Zhang L, Wu DM. Aerodynamic characteristics of 2D WIG flying above sea wave. In: Proceedings of China international boat show and high performance marine vehicles (HPMV) conference, 2003. E13.
[652] Shin MS, Yang S-I, Joo YR, Kim SK, Bae YS, Kim J-H. Performance prediction of the eight passenger class wing-in- ground effect ship. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 108–20.
[653] Shlaustas RYu. Calculation of aerodynamic characteristics of two foils near an underlying surface. Methody vozmuscheni v mekhanike, Irkutsk, 1984. p. 46–58.
[654] Siclari MJ, Carpenter ER. Navier–Stokes computation for a magnetically levitated vehicle (MAGLEV) in ground effect. In: David AC, Mohamed MH, editors. Frontiers of computational fluid dynamics. New York: Wiley; 1994.
[655] Sinitsyn DN. Summary of results of work on creation of Russia's ekranoplans and topical tasks in development of advanced passenger transport ekranoplans. In: Proceedings of the 1st international conference on ekranoplans. St. Petersburg: Marine Technical University; 3–5 May 1993. p. 6–7.
[656] Sinitsyn DN. Summary of the construction of the first commercial ekranoplan, amphistar. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 146–51.
[657] Sinitsyn DN, Maskalik AI, Litinsky LO. The present day state and prospects for the development of commercial ekranoplans. In: Proceedings of the international workshop on ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 163–76.
[658] Skorov SA, Cherniavets VV, Prikhodko GK, Shuvalov VP. Some questions of operational efficiency of ekranoplans. Sudostroenie 1995;0(8–9):3–6.
[659] Sloan HJ, Baker J. Wingship technology and global logistics. Logist Spectrum: J Soc Logist Eng 1995; 29(3):19–31.
[660] Smirnov AI. Effect of proximity of the earth on the aerodynamic characteristics of wing profiles. Trudy VVIA im. N.E. Zhukovskogo 1949;0(334).
[661] Smirnov AI. To the question of determination of circulation and lift of an arbitrary thin foil placed near the ground. Inzhenerniy Sbornik, tom IX, 1951.
[662] Smith A. The radical rada craft. Pacific Ultralights Mon. May 1996, p. 17–9.
[663] Smithey WJH, Papadales Jr BS, Chaplin HR. Effect of turbulent jet mixing on the static lift performance of a power-augmented-ram wing. David Taylor Naval Ship Research and Development Center ASED-389, September;1977.
[664] Sokolov VV. On the contact of two elements. Moscow: Avico Press; 1993.
[665] Sokolov VV. Ekranoplans: perspectives of commercial application. Sudostroenie, 1996. p.94–7.
[666] Sowdon A. Removing the boundary layer on a ground plane. In: Abstract of the 64th general meeting of Ship Research Institute, December 1994. p. 167–72.
[667] Sowdon A, Hori T. Prediction of some aerodynamic derivatives for a wing-in-surface effect. In: Presentation at the 32d aircraft symposium of the Japanese Society of Aeronautical and Space Sciences, Hiroshima, November 1995. p. 4.
[668] Sowdon A. Hori T. An experimental technique for accurate simulation of the flowfield for wing in surface effect craft. Aeronaut J June/July 1996; 215–22.
[669] Standingford DWF, Tuck EO. Lifting surfaces in ground effect. In: Proceedings of the international workshop ekranoplans and very fast craft. Sydney, Australia: The University of New South Wales; 5–6 December 1996. p. 230–43.

[670] Steinbach D. Berechnung der Stromung mit Ablosung fur Profile und Profil Systeme in Bodennahe oder in geschlossenen Kanalen. DFVLRAVA IB 251-77 A02, 1977.
[671] Steinbach D, Jacob K. Some aerodynamic aspects of wings near ground. Trans Jpn Soc Aeronaut Space Sci 1991;34(104):56–70.
[672] Steinbach D. Comment on aerodynamic characteristics of a two-dimensional airfoil with ground effect. J Aircraft 1997; 34(3):455–6.
[673] Stinton D. Aero-marine design and flying qualities of floatplanes and flying boats. Aeronaut J March 1987. p. 97–127.
[674] Stinton D. Wing in ground effect craft: Part II. Ship and Boat International, June 1995. p. 39–45.
[675] Stinton D. Wing in ground effect craft. Part III: Operational qualities of ram-wings, Ship and Boat International, July/August 1995. p. 43–8.
[676] Stinton D, Long-Haul H. Operations using the air–sea interface. In: Proceedings of the international conference on wing-in-ground effect craft. London, Paper no. 10, 4 and 5 December 1997.
[677] Strand T. 150-knot gem cruise, Aerospace Eng April 1962.
[678] Strand T, Brainerd JJ. Design of wing sections for use near the ground. Air vehicle corporation report no. 349, San Diego, 1965.
[679] Suh YB, Ostowari C. Drag reduction due to ground effect. J Aircraft 1988;25(11):1071–2.
[680] Suh SB, Lee ST, Afremov AS. A study of methods for assesing controllability and safety of WIG. In: Proceedings of the annual meeting of the Society of Naval Architects of Korea, Seoul, 13–14 November 1997.
[681] Sullivan MC. Flow breakdown for wings in ground effect. J Aircraft 1978;15(12):859–60.
[682] Sweetman B. Wings over Russia. Popular Sci 1994;245(2): 48–53.
[683] Takahashi T, Fuwa T. WISES design methods and their application. J Kansai Soc Naval Archit, Japan 1994(222):183–90 (in Japanese).
[684] Tan DL, Wang Q. Research on performance of the wingship. In: Proceedings of China international boat show and high performance marine vehicles (HPMV) conference 2005, E14.
[685] Tange J. Mitsubishi bouwt vliegende boot, Politechnisch Weekblad, 7 May 1992.
[686] Tani I, Tamai M, Simidu S. The effect of the ground on the aerodynamic characteristics of a monoplane wing. Rep Aero Res Inst Tokyo 1937; 156.
[687] Tani I, Itokawa H, Taima M. Further studies of ground effect. Reports of the Aeronautical Research Institute, Tokyo Imperial University, no. 158, 1937.
[688] Tanfield Jr. TW. Near surface vehicle. US patent no. 5, 267, 626, December 7 1993.
[689] Tarasov SV, Mikhailov MA. Interactive model of sea waves fro pre-flight preparation of small class-A ekranoplan. In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), 27–30 June 2005, St. Petersburg, Russia, 2005.
[690] Taylor GK. Wing-in-ground effect—the concept and the market. Ship and Boat International, October 1995. p. 49–53.
[691] Taylor GK. Is it a boat? Is it a plane? No!, It is ekranoplan. Mar Model Mon June 1995; 22–5.
[692] Taylor GK. Market focused design strategy: Viable Transport System Or Flight Of Fancy? In: Proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 2, 4 and 5 December 1997.
[693] Taylor GK. Flying in the face of reason: The fact or fantasy of commercial WIG. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 5–28.
[694] Taylor G, Matjasic K. Turning seaways into freeways—the 90-knot zero-wash ferry. In: Proceedings of the PACIFIC 2004 international maritime conference, vol. 1, session 9-WIGs, 2004. p. 242–54.
[695] Taylor G. WIG—what are you waiting for? In: Proceedings of the 8th international conference on fast sea transportation (FAST 2005), 27–30 June, St. Petersburg, Russia, 2005.
[696] The Caspian Sea Monster. Int Defence Rev 1984; 17(9): 1200.
[697] The shape of the future. Mar Eng Rev October 1996; 23.
[698] Thomas, F. Aerodynamische Eigenschaften von Pfeil- und Deltafluegeln in Bodennaehe, Jahrbuch der WGL. 1958. p. 53–61.
[699] Thomas JL, Paulson Jr JW, Margason RJ. Powered Low-aspect-ratio wing in ground effect (WIG) aerodynamic characteristics, NASA TM 78793. Hampton, VA: NASA Langley Research Center; July 1979.
[700] Tinajero AA, Fresh JN. Aerodynamic response of a 7 foot ground effect machine flying over uneven surfaces. DTMB report 1436, Aero report 982, June 1960.
[701] Tomaru H, Kahama Y. Experiments on wing-in-ground effect with fixed ground plane. In: Proceedings of the 2nd JSME-KSME fluids engineering conference, 1990. p. 370–3.
[702] Tomaru H. Experimental investigation of wing-in-ground effect. MS thesis, Institute of Fluid Science, Tohoku University, 1994.
[703] Tomilin VV, Nagapetyan RA, Globenko VM. Design, construction and development of the first passenger ekranoplan Aquaglide. In: Proceedings of the PACIFIC 2004 international maritime conference, vol. 1, Session 9-WIGs, 2004; p. 237–41.
[704] Tomita N. Rocketplane/ekranoplan, the paper presented at the Russian–Japanese seminar on high-speed marine vehicles. St. Petersburg: Marine Technical University; 5 September 1995. p. 36.
[705] Tomita N, Ohkami Y. The extensive use of a take off assist for a rocket plane. AIAA-95-6121, Chattanooga, TN, 1995.
[706] Tomita N, Nebylov AV, Sokolov VV, Ohkami, Y. Performance and technological feasibility study of rocket-powered HTTL-SSTO with take-off assist. In: The 7th AIAA international aerospace planes and hypersonic technologies and systems conference, Norfolk, VA, USA, 1996.
[707] Tomita N, Nebylov AV, Sokolov VV. The concept of heavy ekranoplane use for aerospace plane horizontal take-off and landing. In: Proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 8, 4 and 5 December 1997.
[708] Tomotika S, Nagamiya T, Takenouti Y. The lift of a flat plate placed near a wall with special reference to the effect

of the ground upon the lift of a monoplane aerofoil. Aeronaut Res Inst, Tokyo Imperial Univ 1933;97.
[709] Tomotika S. The lift on a flat plate placed in a stream between two parallel walls and some allied problems. Report of the Aeronautical Research Institute, no. 101, 1934.
[710] Tomotika S, Imai J. Note on a lift and moment of a plane airfoil which touches the ground with its trailing edge. Rep—ARJ Tokyo 1937;10(154).
[711] Tomotika S, Imai I. The interference effect of the surface of the sea on the lift of a sea plane. Report of the Aeronautical Research Institute, Tokyo Imperial University, 12(146), 1937.
[712] Tomotika S, Nagamiya T, Takenouti Y. The lift on a flat plate near a plane wall with special reference to the effect of the ground upon the lift of a monoplane wing. Rep Aero Res Inst Tokyo 156; 1937.
[713] Tonnies E. Effect of the ground on an airplane flying close to it. TM no. 674, NACA, 1932.
[714] Treschevsky VN, Yushin VI. Calculation of aerodynamic characteritsics of thick wings of complex aerodynamic configuration, moving above the boundary of two media. Trudy TSNII imeni A.N. Krylova, vyp. 283, 1977.
[715] Treshkov VK. Approximate method of calculating the interaction of finite span airfoils in unsteady motion above a solid surface. Trudy Leningradskogo Korablestroitelnogo Instituta, no. 80, 1972.
[716] Treshkov VK. Method of calculation of unsteady characteristics of a closed lifting surface. Trudy Leningradskogo Korablestroitelnogo Instituta, Gidromekhanika i Teoriya Korablya, 1980. p. 104–11.
[717] Trillo RL. Taking Advantage of surface proximity effects with aero-marine vehicles. In: Proceedings of the symposium "ram wing and ground effect craft". London: The Royal Aeronautical Society; 19 May 1987. p. 1–6.
[718] Tsvetkov LG. Approximate method of calculating the aerodynamic load distribution of a low flying wing with a fuselage. Trudy Leningradskogo Korablestroitelnogo Instituta, no. 69, 1970.
[719] Tsvetkov LG. A method of calculating the unsteady aerodynamic characteristics of a low flying wing with cylindrical fuselage. Trudy Leningradskogo Korablestroitelnogo Instituta, no. 80, 1972.
[720] Tsvetkov LG. Nonlinear aerodynamic characteristics of a deformable wing flying near a shield. Izvestia VUZov, Aviatsionnaya Tekhnika, no. 2, 1981.
[721] Tuck EO. Irrotational flow past bodies close to a plane surface. J Fluid Mech 1971;98:33–47.
[722] Tuck EO. On air flow over free surfaces of stationary water. J Aust Math Soc Ser B 1975;19:66–80.
[723] Tuck EO. Nonlinear extreme ground effect on thin wings of arbitrary aspect Ratio. J Fluid Mech 1983;136:73–84.
[724] Tuck EO. A simple one-dimensional theory for air-supported vehicles over water. J Ship Res 1984;28:290–2.
[725] Tuck EO. Small gap flows. Report no. NAOE-84-1. Berkeley: Department of Naval Architecture and Marine Engineering, California University, 1984.
[726] Tuck EO, Dixon A. Surf–skimmer planing hydrodynamics. JFM 1989;205:581–92.
[727] Turner T. A moving belt ground plane for wind tunnel ground simulation and results for 2 jet-flap configurations. NASA TN D-4228, 1967.
[728] Tudem U. Air supported vessels (ASV)—an innovative approach to reduce hull resistance and improve performance-suitable for various naval and commercial applications. In: Proceedings of the world maritime technology conference, London, 6–10 March 2006.
[729] Udalov KG, Panatov GS, Fortinov LG. Airplane VVA-14. Moscow: Avico Press; 1994.
[730] USSR fast ferry projects: Part 2, Fast Ferry International, November 1991, p. 13–7.
[731] Vachasov YeP, Kurochka GF. Analysis of the longitudinal disturbed motion of a surface skimmer. Samolyetostroeniye i Tekhnika Vozdushnogo Flota 1972;0(29):7–13.
[732] Vanderplaats GN, Park CS, Balabanov V. Multidiscipline design optimization of WIG vehicles. In: Proceedings of the 1st international symposium on WIG crafts. Korea: Sofitel Ambassador Seoul, 8 November 2005. p. 67–76.
[733] Vasilevsky I, Kirillovykh V, Naritsin B, Privalov E, Alexeev V. View points of ekranoplan designers regarding some classification issues. In: Proceedings of the international workshop WISE up to ekranoplan GEMs. Sydney, Australia: The University of New South Wales; 15–16 June 1998. p. 114–24.
[734] Vasilevskiy IM, Denisov VI, Nebylov AV. Automatically controlled ekranoplans: experience and problems. In: The 16th IFAC symposium on automatic control in aerospace. St. Petersburg, 2004. p. 519–24.
[735] Vasil'eva VV, Voitkunskiy YaI, Tkach AYa. Unsteady hydrodynamic characteristics of bodies moving near a surface. Trudy Leningradskogo Korablestroitelnogo Instituta 1976(104):17–23.
[736] Velovich A. Pilot blamed for Russian WIG crash. Flight Int, January 1993.
[737] Vizel EP. Investigation into peculiar features of the flow past wings of small aspect ratio near the ground. Tezisy dokladov na XX nauchnotekhnicheskoi konferentsii po teorii korablya, Leningrad, Sudostroenie, vyp. 156, 1971. p.79.
[738] Vizel EP. Investigation of free vortices of a wing of small aspect ratio with end plates near the ground. Ucheniye Zapiski TSAGI, M 1971;II(3):12.
[739] Voitkunskiy YaI, Faddeev YI, Polischuk MA. Influence of viscosity on profile lift and drag near the ground. In: Proceedings of the Leningrad Shipbuilding Institute 1967(65).
[740] Volkov LD, Pashin VM, Ponomarev AV, Sinitsyn DN, Chubikov BV. USSR research and design effort in the development of marine ekranoplans. Transportation capability of these in different water areas. In: Proceedings of the intersociety high performance marine vehicle and exhibit—HMPV'92, Arlington, VA, 24–27 June 1992.
[741] Volkov LD. Numerical investigation of nonlinear characteristics of foils of different shapes in motion near the ground. In: Proceedings of the 1st international conference on ekranoplans. St. Petersburg: Marine Technical University; 3–5 May 1993, p. 37–47.
[742] Volkov LD, Russetsky AA. Ekranoplans: problems and perspectives. Sudostroenie J 1995(1):1–6.
[743] Unov SV. Aperiodic motions of a thin foil in compressible fluid at small istances from a solid boundary. rudy Chuvashskogo Universiteta, Dinamika Sploshnoi Sredy s Nestatsionarnymy Granitsami, 1984. p. 113–7.

[744] Walker RL, Berman HA. Wind tunnel investigation of PAR-WIG model. CRDKNSWC/RD-22-93/98, March 1993.
[745] Wang Q-X. Flow around an unsteady thin wing close to curved ground. J Fluid Mech 1991;226:175–87.
[746] Wang EG, Zhu LT, Song MD. Development, operation and experience on the practical wig effect aircraft "Tianyi-1". In: Proceedings of China international boat show and high performance marine vehicles (HPMV) conference 2003, E21.
[747] Warmkessel B, Barker E. Force projection vehicles. In: Proceedings of the US Naval Institute, January 1993. p. 89–91.
[748] Waters DM. Thickness and Camber effects on bodies in ground proximity advanced road vehicles aerodynamics, Cranfield, 185-206, 1973.
[749] Werle H. Simulation de l'Effect de Sol au Tunnel Hydrodynamique. La Recherche Aerospatiale no. 95, 1963.
[750] Wetmore JW, Turner Jr LI. Determination of ground effect from tests of a glider in towed flight. NACA TR-695, 1940. p. 13.
[751] White HE. Wind tunnel test of a low aspect ratio wing in close proximity to the ground. Aero report 1056, 1974.
[752] Maskalik AI, Treschevsky VN. Wingship compendium, Under contract no. 14-92-C-0240, Office of Naval Research, 1992.
[753] Wohl, R. Closing the technology gap. Defence Sci July 1988; 17–20.
[754] Wukowitz S. Power augmentation: Coanda effect and RAM. AIAA paper 1981.
[755] Yukhimenko AI. Effect of profil shape on aerodynamic characteristics of a wing near a shield. Gidrodinamika Bolshikh Skorostey, 1966.
[756] Yuan CH, Ye YL. Study on the space motion of wing-in-ground effect craft. In: Proceedings of China international boat show and high performance marine vehicles (HPMV) conference, 2003. E12.
[757] Yun Liang. The development of air cushion technology—from static cushion (ACV) to dynamic air cushion technology (AWIG). In: Proceedings of China international boat show and high performance marine vehicles (HPMV) conference, 2003. E11.
[758] Yushin VI, Tomnitsky MYu. Method of calculation of thick wings of complex configuration, moving near the interface. Tezisy Dokladov na XXIV nauchnotekhnicheskoi conferentsii po teorii korablya, 1975. p. 178.
[759] Yushin VI. Use of continuous vortex layers in treatment of the problem for the incompressible flow past a contour Voprosy sudostroeniya, ser. Proektirovanie sudov, vyp. 29, 1981.
[760] Zhigalko EF, Nebylov AV. Ekranoplan aerodynamic scheme investigation in application to new tasks. In: Proceedings of the aviation technology, no. 2, Russian University, 1998.
[761] Zhilin YuL. A wing of minimum induced drag near a ground. Izvestia Akademii Nauk SSSR, Ser. Mekhanika i Mashinostroeniye 1963(1):148–9.
[762] Zhukov VI. Static longitudinal controllability of ekranoplan with account of the thrust moment. Moscow: Trudy TSAGI; 1977.
[763] Zhukov VI, Ivlieva ZV. Approximate determination of the flow down-wash at the tail plane for calculation of additional forces and moments acting on an ekranoplan in unsteady motion. Moscow: Trudy TSAGI; 1983.
[764] Zhukov VI. An investigation of stability of ekranoplan with use of the method of small increments. Moscow: Trudy TSAGI; 1983.
[765] Zhukov VI. On conditions of efficient improvement of characteristics of longitudinal stability with use of the system of automatic control. Moscow: Trudy TSAGI; 1983.
[766] Zhukov VI. Pecularities of aerodynamics, stability and handling of ekranoplanes. In: Proceedings of the international conference on wing-in-ground effect craft, London, Paper no. 17, 4 and 5 December 1997.
[767] Zimmerman CH. Characteristics of Clark Y airfoils of small aspect ratios. NACA report 431, 1932.
[768] Zinchuk PI. Motion of a V-shaped wing with optimal distribution of loading near the ground, in Gidrodinamika nesuschikh poverkhnostei. Kiev, Naukova Dumka, 1966. p. 174–87.
[769] Zinchuk PI, Neznamov VN. Experimental investigations of hydrodynamic characteristics of a wing with curvilinear lateral axis near the ground. Kiev, Gidromehkanika, vyp. 27, 1974. p. 13–6.