Chapter 2
WIG Craft Development

Introduction

Our aim in this chapter is to introduce the reader to the WIG development programmes carried out in a number of countries in the last half of the twentieth century and up to date, so as to give a historical perspective on the origins of the technology.

Prior to this, ground effect was already being used for flying machines. In 1903, the Wright Brothers flew relatively long distances in the surface effect zone with their biplane. They were aware of the higher lift forces when gliding close to the ground, but were aiming to fly higher into the air.

Later, in the mid-1930s, Kaario of Finland started to build and test craft operating in strong ground effect, see [1]. Kaario's concept was for a high-speed boat that could glide over ice as well as water. However, due to greater interest in the aeronautical industry for development of passenger aircraft, floatplanes and seaplanes, the captured air bubble craft built by Kaario was not developed further. It was 30 years later, at the beginning of the 1960s, that Alexeyev began his development of Ekranoplans in Russia. The Russian R&D was the world's first major WIG programme, targeted at a new military capability, so we will begin by reviewing it together with the steps leading up to it.

Russian Ekranoplan Development

Two major research and development initiatives were undertaken in Russia to increase ship speeds in the twentieth century. The first initiative in the 1940s and 1950s was aimed at breaking through the so-called wave-making barrier and so decrease wave-making resistance at high speed. The second initiative was to lift a marine craft completely from the water surface to glide just above it.

All displacement-type marine craft cause a pressure wave pattern as they move through the water. This wave-making exhibits itself as a water surface deformation and also as a resistance to motion that increases in proportion with the square of forward speed. High-speed craft with inclined, flat lower surfaces rise out of the displacement mode into "planing" mode once the dynamic pressure of the water on

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the inclined underside becomes high enough to balance the craft weight. The power needed to enable a boat to accelerate to planing mode is very high and was only achievable until recently by small craft such as racing powerboats and military fast patrol boats.

In the 1950s, marine engineers in Russia and Switzerland adopted an alternative way to lift the hull of a boat clear of the water, by attaching lifting foils under the hull to produce hydrodynamic lift in a similar way to the wings of an aeroplane. In water, 800 times denser than air, the foils can be relatively small. This idea was developed in Russia by a naval architect, R.Y. Alexeyev.

The hydrofoil craft, as defined by Alexeyev, had shallow submerged hydrofoils located under the water surface, however still in the region where the pressure field around the foil is strongly affected by the water surface itself. The hydrofoil lift reduces rapidly as the draft of the hydrofoil decreases and the hydrofoils approach the water surface. In Russia, this is called the Alexeyev effect after its discoverer. Alexeyev was the first to use this effect together with a tandem configuration of hydrofoils to provide longitudinal stability, avoiding the problems that occurred on very early hydrofoil prototypes. This success led to the building of significant numbers of both river and seagoing hydrofoil passenger ferries in the Former Soviet Union in the period from 1949.

A whole series of different hydrofoils were developed and built in series production, including the river craft “Volga”, “Raketa”, “Meteor”, “Sputnik”, “Chaika”, “Byelorus”; and seagoing hydrofoils “Kometa” and “Vikhr”. The passenger capacity of these craft was from about 30 up to 300 seats. They had service speeds up to 100 km/h. More than one thousand such craft have been constructed in the Former Soviet Union and operate in domestic rivers, lakes and seas. A significant number have also been exported to over 30 other countries for service on rivers such as the Danube and Rhine and in the Mediterranean and Aegean seas.

Hydrofoils can operate at speeds up to 130 kph; however, at this speed another barrier is met – the so-called cavitation barrier – which limits the further increase of speed due to the cavitation phenomenon that occurs on the hydrofoil’s upper surface. This effect reduces the lift force and increases drag of the foil. The effect is similar to propeller cavitation. When the pressure on the foil’s upper surface drops below water vapour pressure, a bubble of vapour is formed and the lifting force reaches a limit. As forward speed increases, the cavity will grow and limit the lifting force, unless the foil geometry is specifically designed to operate in this mode. Such foils have a sharp leading edge form and are less efficient at speeds below the cavitation region [1]. Hydrofoil craft designed for very high speeds therefore require much higher power density and are less economical for commercial service.

The new idea proposed by Alexeyev at the end of the 1950s was to put aircraft wings onto a high-speed boat and lift the hull out of the water to glide just above it supported by aerodynamic lift. Such a concept would also require aerodynamic propulsion. It was the logical extension of his shallow submerged hydrofoils providing hydrodynamic lift to clear the hull from the water surface.

A most important contributor to stable flight is lift force variation with the distance from the foil to the water surface (screen or “ekran” in Russian), which allows a WIG craft to fly at a steady clearance height, the most important design challenge for WIG craft [2]. The shallow submerged hydrofoil and aerofoil close above the water surface can be considered as a mirror image of each other. In the case of a surface piercing hydrofoil (Fig. 2.1), the lift force of the foil decreases with the decrease of the foil draft. In the case of an airfoil (Fig. 2.2), the lift force increases with the decrease of flying height of the wing.

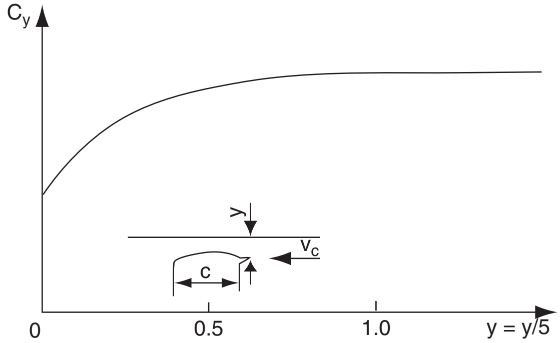


Fig. 2.1 Lift coefficient versus relative immersed depth for hydrofoil craft

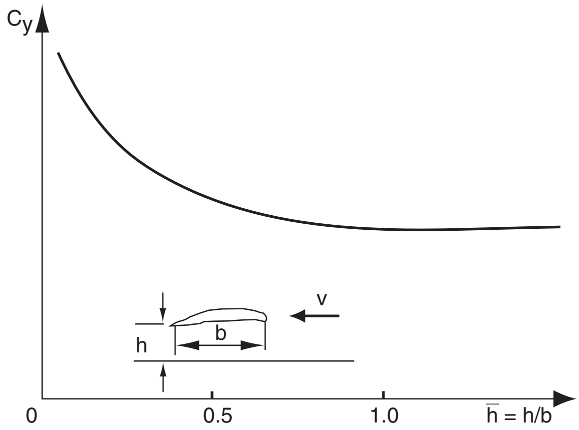


Fig. 2.2 Lift coefficient versus relative flying for WIG

Alexeyev together with the team at his design institute designed and constructed the first WIG test craft, SM-1, in 1960 (in Russia, this designation stood for self-propelled model number 1), with twin wings in a tandem arrangement and weighing 2.8 t (Fig. 2.3). The design was derived from his shallow submerged hydrofoil craft [3]. SM-1 had a 20-m long cigar-shaped fuselage and tandem lifting wings at amidships and at the stern. Side plates in the form of wing tip floats were installed on the main wing and tail wing to reduce the tip vortices so as to increase the lift/drag ratio of the craft. Power was provided by a jet engine mounted above the fuselage aft of the forward wing. SM-1 had a crew of three and was tested over calm water

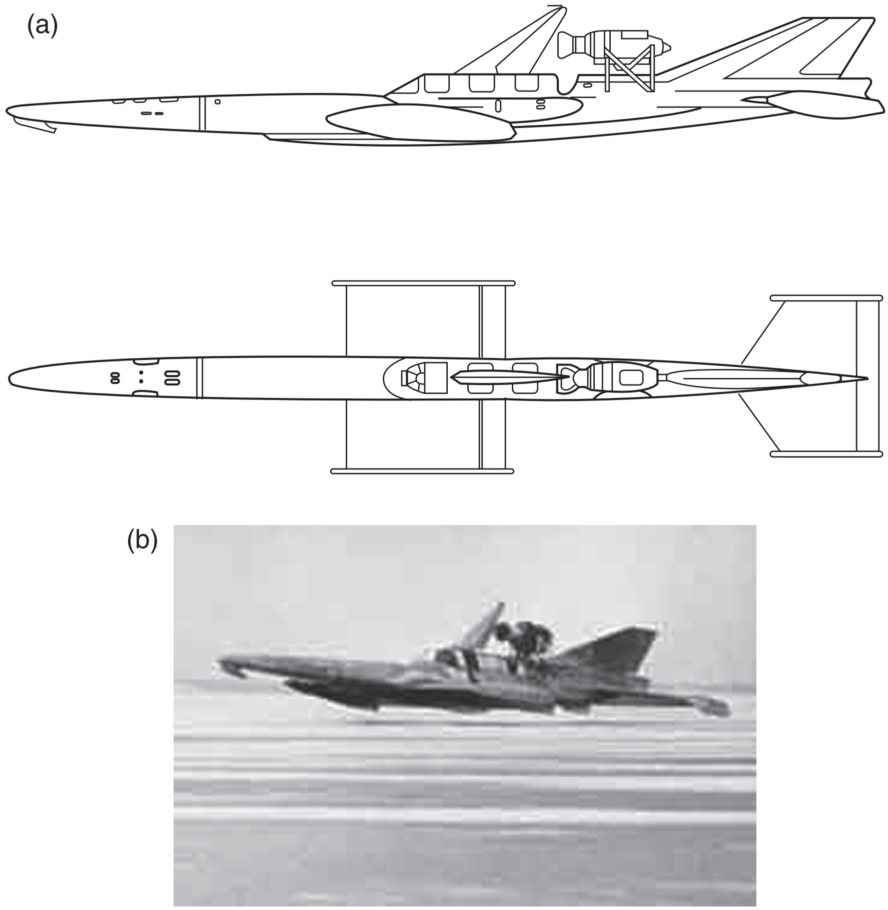


Fig. 2.3 SM-1 (**a** diagram, **b** pic)

at speeds of 200 km/h. It first flew on 22 July 1961. The trials of this craft showed up the problems of the low mounted rear wing to provide steady stabilisation. The rear wing of SM-1 operated directly in the rather unsteady slipstream of the forward wing, so causing the craft to be unsteady in pitch.

SM-1 proved the basic principles; however, it also demonstrated several problems with the configuration, as well as the pitch instability. It had a very hard ride due to high reaction forces/accelerations to wave surface undulations and a very high take-off speed from the water surface (about 150 km/h). It also had rather low pitch stability. SM-1 crashed in January 1962 from engine failure when in a climb manoeuvre. All the crew survived the crash without injury.

Modification of the tandem airfoil arrangement could not solve the "hard" ride problem as all the lifting surfaces of such a wing system operate in strong ground effect and interfere with each other. Alexeyev developed a new aerodynamic arrangement to overcome the problems of SM-1. In the new arrangement one main wing supported the craft in the ground effect region and another horizontal tail stabiliser wing was mounted at the top of a vertical fin outside ground effect to maintain positive longitudinal stability. A first step was also taken by Alexeyev to decrease take-off speed by mounting a jet engine in the bow to deliver pressurised air through a diffuser system under the main wing giving added static lift to the craft.

These design developments were built into a second test craft, the 5 t SM-2 completed in March 1962 (Fig. 2.4a, b). This craft was similar in size to SM-1 and was demonstrated to the President of the USSR Nikita Khrushchev, gaining his support for the Ekranoplan development programme.

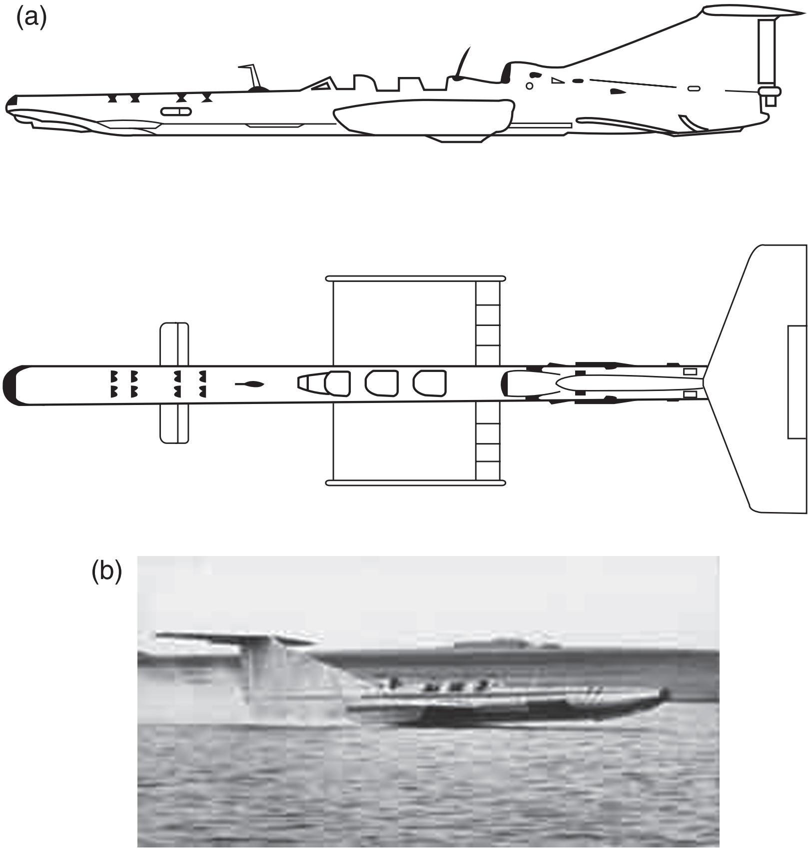


Fig. 2.4 SM-2 (**a** diagram, **b** pic)

The original SM-2 was damaged in a hangar fire and was subsequently modified and given the designation SM-2P after installation of a high mounted rectangular tail wing. The tail wing size of SM-2P was increased compared to tandem winged SM-2, and the RU-19-300 jet engine producing about 1 t of thrust was enclosed in a nacelle at the base of the vertical tail fin. A second RU-19-300 was mounted in the nose and provided jet air augmentation to the main-wing lift from a bank of

Table 2.1 The initial series of Ekranoplan prototypes

	SM-1	SM-2P	SM-3	SM-4	SM2-P7
Build year	1961	1962	1962	1963	1964
Length (m)	20.0	20.0	14.5	20.0	19.4
Main wing span (m)	4.50	5.25	3.80	7.50	9.4
Tail wing span (m)	3.70	6.70	4.10	7.30	8.5
Tail height (m)	3.15	3.40	2.80	3.60	3.5
Hull breadth (m)	1.0	0.9	0.9	0.9	0.9
Hull height (m)	1.4	1.5	1.3	1.96	1.6
Draught (m)	0.3	0.4	0.3	0.5	0.4
Aspect ratio, main	1.26	1.73	0.48	2.0	1.73
Tail	1.35	2.00	2.00	2.0	2.0
Pilot and passengers	1	1	1	1	1
AUW (t)	2.83	3.20	3.40	4.80	6.3
Thrust (t)	1.0	1.8	1.0	3.0	2.0
Engine	1 off	1 off		1 off	
stern	TS-12L	RU-19-300		KR7-300	
Engine		1 off	1 off	1 off	1 off
bow		RU-19-300	RU-19-300	RU-19-300	KR7-300
Take-off speed (kph)	170	160	140	140	140
Maximum speed (kph)	270	270	180	230	270
Cruise speed (kph)	250	250	160	200	250
Flying height (m)	0.5–1	0.5–2	0.5–2	0.5–2.5	0.5–2.5
Maximum seastate (m)	0.5	0.5	0.5	0.7	1.0

nozzles halfway between the nose and the wing. This craft showed that the revised configuration was stable in flight (see Table 2.1 above for characteristics of the early series of craft including SM-2P).

Later in 1962, SM-3 was designed and built (Fig. 2.5a, b). This developed the configuration of SM-2 further, with a much longer, low aspect ratio main lifting wing and smaller tail wing. The crew of three had enclosed cockpits. The main jet engine intake was moved right forward to the nose of the fuselage, and the exhausts from the single RU-19-300 jet blown underneath the leading edge of the main wing. SM-3 began to explore the potential for higher lifting capacity craft. Unfortunately, the low aspect ratio wing did not appear to offer the ideal solution, particularly at higher speeds. Above about 1.5 m flying height the yaw stability of the craft was insufficient for steady flight. Clearly the low aspect main wing was only suitable for small ground clearance concepts.

SM-3 was succeeded in 1963 by the SM-4 (Fig. 2.6a, b), based on the SM-2 configuration, but using a larger KR7-300 jet in the bow driving the lift enhancing system. This jet had a thrust of 2 t, compared to the RU-19-300s 1 t. The maximum take-off weight of this craft was 4.8 t compared with SM-2 at 3.2 t.

SM-4 performance was so encouraging that the design bureau began plans to build a very large WIG, the KM late in 1963 (Fig. 2.7). Prior to building the KM itself, a 1:4 “model” was built. This was the test craft SM-5 (Fig. 2.8). SM-5 had a similar configuration to SM-4, powered by two KR7-300 jet engines and a take-off

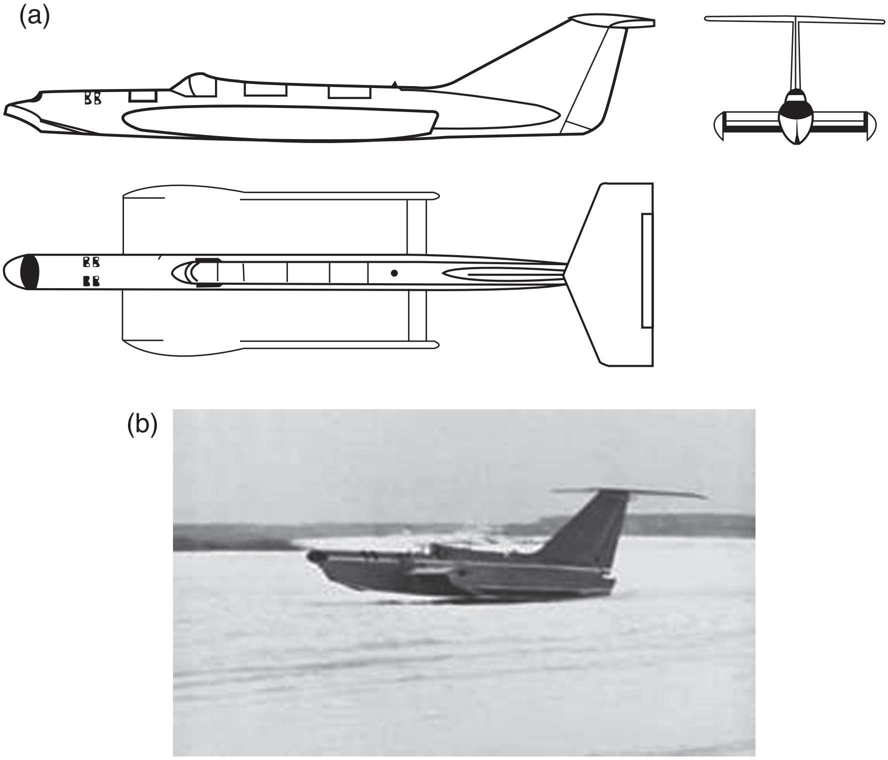


Fig. 2.5 SM-3 (**a** diagram, **b** pic)

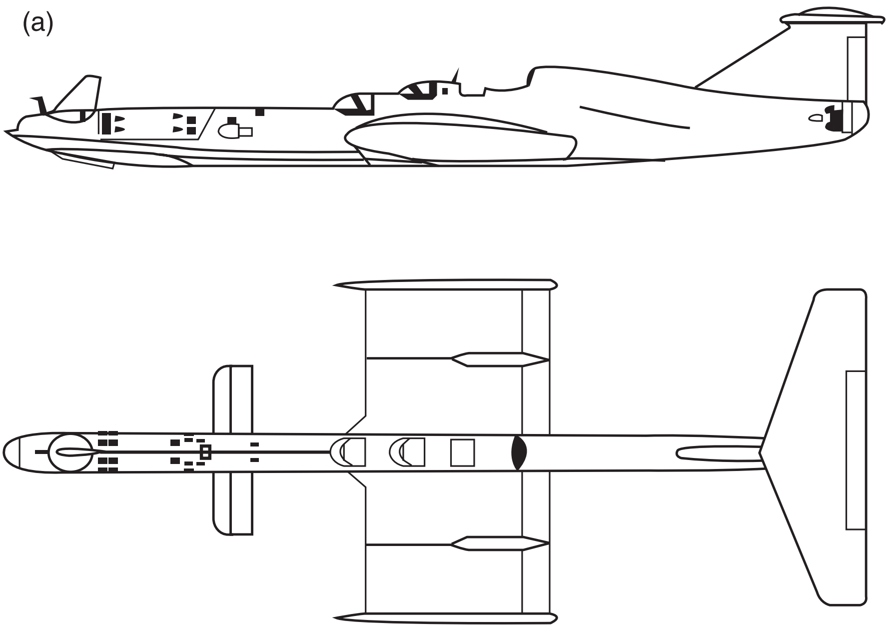
weight increased to 7.3 t. The blower nozzles at the bow were moved higher so that at high speed the efflux would not destabilise the aerodynamics of the main wing.

Tests with SM-5 were short lived as the craft crashed in 1964, unfortunately killing the pilot. Flying against a strong wind during a trial run, the craft started to gain height. The pilot increased power instead of reducing, further gaining height and losing stability, after which the craft ditched.

Also in 1964, a further new test craft was built with revised bow jet blowers closer to the main wing and higher aspect ratio tail wing, the 6.3 t SM-2P7 (Fig. 2.9), with a single bow-mounted KR7-300 for power. This craft was able to cruise at 250 km/h with a wing efficiency *K* of 10–11. Take-off speed was approximately 140 km/h after a 600-to 800-m run.

This work completed the research targeted at developing the very large cargo and personnel carrier KM, so that further research craft could look at configurations suitable for smaller logistics craft. The SM-6 was the first of these, a smaller scale version of the Orlyonok production design. SM-6 (Fig. 2.10) was designed and built in 1972, following completion of KM, so that experience with the much larger craft could be included.

(a)



(b)

Fig. 2.6 SM-4 (**a** diagram, **b** pic)

Extending the fuselage to 31 m and the main wingspan out to 14.8 m, SM-6 used a turbo-propeller gas turbine AI-20 K at the top of the tail fin for main propulsion and a revised bow blower system also powered by two RD-9A jets for lift augmentation. This craft operated at 26.5 t at speeds up to 350 km/h and had an endurance of 700 km.

In parallel with this work, a further quarter-scale prototype of the KM was built in 1967 with similar specifications to SM-5 but with a high dihedral tail wing, and bow engine intake modified to reduce spray ingestion. This craft had the designation

Fig. 2.7 KM

Fig. 2.8 SM-5

Fig. 2.9 SM-2P7

SM-8 (Fig. 2.11). Test prototypes designated SM-9 and SM-10 were also built, but are related to the Volga-2 programme, see Table 2.2 .

Fig. 2.10 SM-6

Fig. 2.11 SM-8

KM or "Caspian Sea Monster"

Normally, a medium-size craft weighing 50–100 t would be designed and constructed following the successful self-propulsion tests of a craft such as the SM-5 and SM-2P7. Alexeyev believed that the aerodynamic and hydrodynamic characteristics were predictable enough that a step directly to a production craft was possible. He was able to convince the Russian Navy of this approach and gain their support for funding the 500-t KM immediately. In Russian KM stands for "Naval Ship Prototype", not "Caspian Sea Monster" [4]. The craft was 92.3 m overall length, 37.6 m maximum width, 22 m maximum height and weighed 544 t, almost twice that of the Boeing 747 jet airliner models available at that time, then the largest aircraft in the world.

The KM accommodated 900 marines and flew at a maximum speed of 300 knots (470 kph) at an optimal flying height of between 4 and 14 m. Eight VD-7-NM turbojet engines with 13 t thrust each were mounted at the bow for starting and

Table 2.2 Development series for the KM Ekranoplan

	SM-5	SM-8	KM
Build year	1963	1967	1966
Length (m)	18.0	24.5	92.4
Main wing span (m)	9.5	9.5	37.8
Wing area (m^2)			662.5
Tail wing span (m)	9.5		
Tail height (m)	5.5	5.5	21.8
Hull breadth (m)	2.0		
Hull height (m)	2.5		
Hull draught (m)	0.6		
Aspect ratio, main	2.0	2.0	2.0
Tail	2.0	2.0	2.0
Pilot and passengers			3 + 900
AUW (t)	7.3	8.1	544
Thrust (t)	4.0	4.0	104 + 26
Engine stern	1 off KR7-300	1 off KR7-300	2 off VD-7 M
Engine bow	1 off KR7-300	1 off KR7-300	8 off VD-7
Take-off speed (kph)	140	140	140
Maximum speed (kph)	230	220	500
Cruise speed (kph)	200	200	430
Flying height (m)	1–3	1–3	4–14
Maximum seastate (m)	1.2	1.2	3.5
Range (km)	n/a	n/a	1,500

take-off, and two VD-7-KM turbojet engines with 13 t thrust each were mounted at the stern for cruising. More detailed specifications can be found in Table 2.1.

The design was completed at 1963–1964 incorporating the results from SM-5 and SM-2P7. Some corrections to the craft structural design were also made based on the tests of the smaller prototypes. The KM was constructed at the “Chikarov” Naval Construction Facility nearby to Gorky city and was completed in 1966 (Fig. 2.7).

The newly launched craft was towed to the WIG test base on the Caspian Sea coast through the Russian river system for its sea trials. The first flight was on 18 October 1966. It lasted just under an hour and tested flight at clearances up to 4 m. Take-off speed was not above 140 km/h, and the craft proved it could fly stably at a cruise speed of 450 km/h at a flying height of 3–4 m as well as over waves of 3 m height in later tests.

Take-off is achieved by running the eight bow-mounted jet engines with thrust nozzles turned down to blow under the main lifting wing at maximum power. Once lifted from the sea surface, the nozzles can be turned horizontal to provide more thrust to accelerate. Once at cruise speed they can be throttled back and the rear-mounted cruise engines used for propulsion.

When stopping, the reverse procedure is employed. First, power is reduced so that craft speed can be slowed to about 210 km/h and flying height reduced. The bow jets’ nozzles are then rotated down to augment the lift force. The cruise engines are shut down and the speed slowed so that the craft settles on its dynamic cushion. Subsequently the hull touches down at about 120 km/h and planes down to displacement mode at 30 km/h or so.

The KM did not have automatic flight controls, so all of these procedures and the rather active adjustment of flight controls to maintain steady flight at cruise were carried out manually by the flight crew.

The KM generated very heavy spray at low speeds (Fig. 2.12), and in addition the bow turbines were prone to bird strike. Intake shields were fitted to the bow turbines, and the cruising engines moved from the base of the tail fin to a pylon between the bow engines in 1979.

Fig. 2.12 KM at low-speed generating spray

During one trial, in order to demonstrate good ditching stability, Alexeyev ordered the engines deliberately stopped and let the craft ditch without control intervention. The craft was able to land horizontally and safely. It gave the pilots on board at the time much improved confidence, flying at such high speed close to the surface. The craft also had excellent manoeuvrability such that it could complete a 360° turn by banking as far as the inner wing tip touching the water surface.

Mr. Alexeyev was a very experienced airplane pilot himself, so he generally explained the flying features of the WIG craft to pilots from the Russian Air Force himself. In particular, it was his experience that

> As an airplane pilot, one often realizes that the airplane would be safer if it would be less interactively flown. However, on a WIG, it is to the contrary. If a WIG rises above the ground effect region, the pilot should take measures to decrease the flying height, such as to throttle down the engine speed or decrease thrust so as to decrease the speed of craft below the normal cruising speed of 250 km/h temporarily. When the craft is to be brought to a stop from cruising speed, the pilot must first throttle back the stern engines, while changing the bow engines from cruising mode to blowing air mode and establish the air cushion under the wings. At the same time the main wing flap has to be dropped down. The craft will then touch down smoothly and safely.

If the procedures for adjusting bow thrusters to establish cushion lift augmentation when slowing down are not followed, a WIG may decelerate very quickly on touching the water and damage can occur, as happened on earlier test craft, and "KM" itself in 1980 [4]. In December of that year, the pilot attempted to change to cruise mode before having lifted off. The craft crashed into the sea and sank. The crew were safe, but recovery attempts for the craft were unsuccessful, the structure having broken up as it crashed and sank in the Caspian Sea.

Over its 14-year operational career, the KM wore a number of different tail numbers as it progressed through different test phases. This rather confused the western military observers, who thought that there may be up to ten KM craft!

UT-1

The SM series of test craft and the KM were very expensive craft to operate and so it was decided to build a low-cost pilot training Ekranoplan, the UT-1 (Fig. 2.13). This was a small craft with a single aircraft piston engine driving a propeller mounted above the central fuselage or hull. UT-1 was used as the test bed for the hydro-ski or shock absorber ski. This was a hinged plate mounted under the centre of the hull at the place where a step would be introduced on a single step hydroplane. The ski could be adjusted in angle and was used to improve take-off performance (reducing power and take-off run distance). Its success led to development of the much larger skis used on Orlyonok, Lun and Spasatel.

Fig. 2.13 UT-1

Orlyonok and Lun

Successful trials and operation of KM showed longitudinal and transverse stability in flight to be adequate, and its manoeuvrability and course stability satisfactory to the requirements of the Soviet Navy. Alexeyev and his colleagues therefore began design of a smaller military WIG, the heavy-duty landing craft "Orlyonok". Their initial task was to complete a small-scale prototype, as described above, the SM-6, at 0.5 linear scale to the production design.

Leading particulars of Orlyonok are as shown in Table 2.3 and below. The craft profile as well as some cross sections of the craft are shown in Fig. 2.14 and the general arrangement in Fig. 2.15.

Maximum length, width and height (m)	58, 31.5, 16
Maximum take-off weight (t)	140
Payload (t)	250 marines or 20 t military equipment, which could enter or exit from bow ramp
Lift engines	Two HK-8 gas turbine turbofan engines located at the bow with maximum thrust of 98KN, the nozzles of which can be rotated down to provide a positive cushion pressure under the main wings in take-off and used for additional thrust when rotated horizontal at cruising speed
Propulsion engines	One HK-12 gas turbine turbo-propeller engine rated at 11,030 kW located at the top of the tail fin driving contra-rotating propellers
Performance	The craft can operate at maximum speed of 350 km/h, at flying height of 2 m with a maximum range of 1,000 km

Orlyonok was designed to come ashore onto a concrete apron at its main operating base, so was fitted with a wheeled undercarriage. There are two rotating bow wheels and nine main support wheels located under the main hull. The bow wheels can be retracted with aid of hydraulic systems into the main hull and behind a large hydro-ski installed close to the hull centre. The rotating bow thruster nozzles (1), landing gear (2), hydro-ski (3), together assures efficient launch and landing operation and take-off performance. From Figs. 2.14 and 2.15, one can see the contra-rotating propellers mounted at the top of the tail fin for cruising and flaps on the main wings for improving stability.

The aspect ratio of Orlyonok's main wing is also extended from 2.0 (KM configuration) to 3.07 so as to improve the high-speed aerodynamic properties of the wings. This craft layout was called airplane style in the Former Soviet Union and achieved the following characteristics:

- Main-wing aerodynamic efficiency, $K = 15.0$, in operation close to the ground or water surface and 9.0 for the higher clearance strong ground effect zone
- Stability and self restoring characteristics to perturbations are acceptable over a wide range of operating pitching angle and flying height, including the ability to fly above the ground effect zone
- Manoeuvrability of the craft in the longitudinal and lateral planes that met the requirements specified by the Soviet Navy staff
- Range when flying at cruise speed in ground effect is 1,000–1,500 km
- Craft of Orlyonok size can take off and touch down on the sea surface in 1.5-m waves

Table 2.3 Development series for the Orlyonok, Lun and Spasatel

Data	UT-1	SM-6	Orlyonok	Lun	Spasatel
Build year	1967	1972	1973–1980	1986	1996
Length (m)	9.7	31.0	58.1	73.8	73.8
Main wing span (m)	5.4	14.8	31.5	44.0	44.0
Tail wing span (m)		12.2			
Tail height (m)	2.0	7.9	15.9	19.2	19.2
Hull breadth (m)			4.0		
Hull height (m)					
Draught (m)	0.2	0.6	1.5	2.5	2.5
Aspect ratio, main	2.2	2.8	3.0	3.0	3.0
Tail			4.0	4.0	4.0
Pilot and passengers	1		9 + 250	9 + 19 + 150	9 + 19 + 650
AUW (t)	0.9	26.5	140	380	390
Payload			20	137	143
Thrust (t)	140 shp	4.2 + 3,750 shp	2 × 10.5 + 15	78 + 26	78 + 26
Engine stern	1 off M332	1 off AI-20 K	2 off NK8-4	2 off NK-87	2 off NK-87
Engine bow		2 off RD-9A	1 off NK-12MK	6 off NK-87	6 off NK-87
Performance					
Take-off speed (kph)					
Maximum speed (kph)	170	350	400	550	550
Cruise speed (kph)	140	300	375	450	450
Flying height (m)	0.1–0.5	0.5–1.5	0.5–5	1–5	1–5
Maximum seastate (m)	0.3	1.0	2.0	>3.0	>3.0
Range (km)		700	1,500	2,000	3,000

The relatively low aerodynamic efficiency of such craft by modern standards can be explained by

(a) Using a wing configuration similar to an airplane while using a low aspect ratio, AR = 2.0–3.0
(b) The large area needed for tailplane, fin and rudder for pitch and yaw stability

Orlyonok's Accident

The prototype Orlyonok was completed in 1974. Sea trials were carried out in some hurry, as the Navy wanted immediate delivery. Once the sea trials had started the deputy minister of shipbuilding together with all members of the approval committee went on board to observe the testing. The sea nearby the Caspian Sea Test Base was rough, with a relative large swell because of a heavy storm that had passed

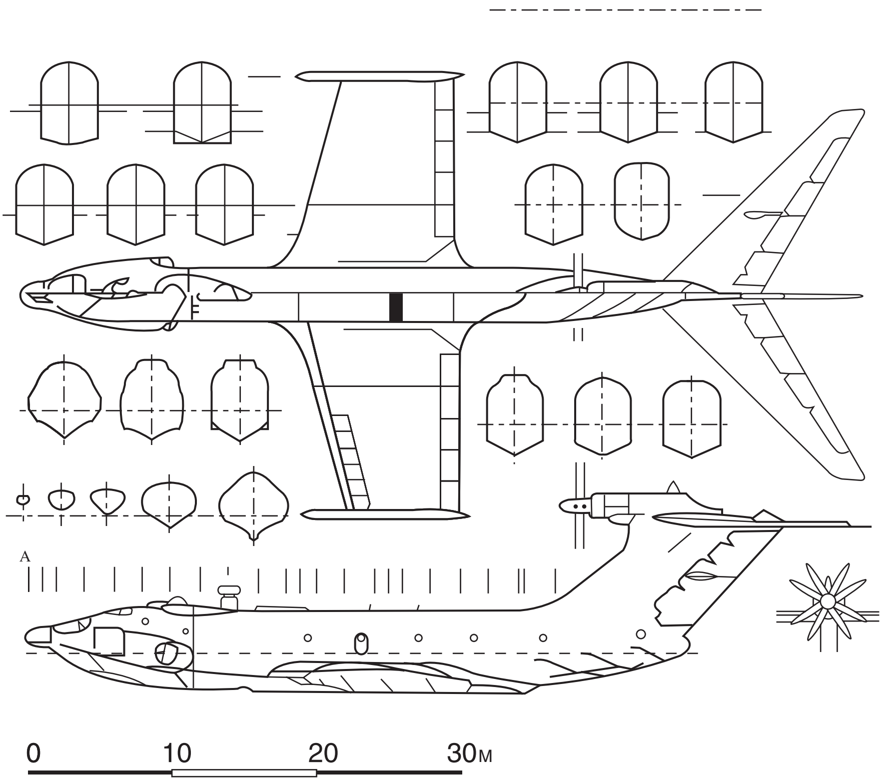


Fig. 2.14 Section profile of Russian WIG-type "Orlyonok"

through the area several days before. The length of swell was approximately equal to that of the craft.

After several runs, the craft made a strong impact with a wave at the stern part of craft, causing serious damage. Mr Alexeyev went aft to investigate the extent of the damage, opened the upper hatch and made an observation towards the stern part of the craft. He then returned to the cockpit and sat down in the pilot's seat to take personal control. The pilot himself was almost scared out of his wits. Mr. Alexeyev throttled up to the maximum output of the bow engines and drove the craft back to the base, a distance of almost 40 km from the test location.

The craft was seriously damaged over the whole of the stern area, including the fin and tailplane. The stern propulsion engine was also damaged. At the subsequent enquiry board meeting analysing the reasons for the incident, the members of committee, including the deputy minister of shipbuilding, concluded that the hull strength was unsatisfactory. Alexeyev, however, insisted that the main reason causing this accident was incorrect handling by the pilot.

The remainder of the committee did not agree, referring to another similar casualty that happened to one of the smaller test craft. The members of committee

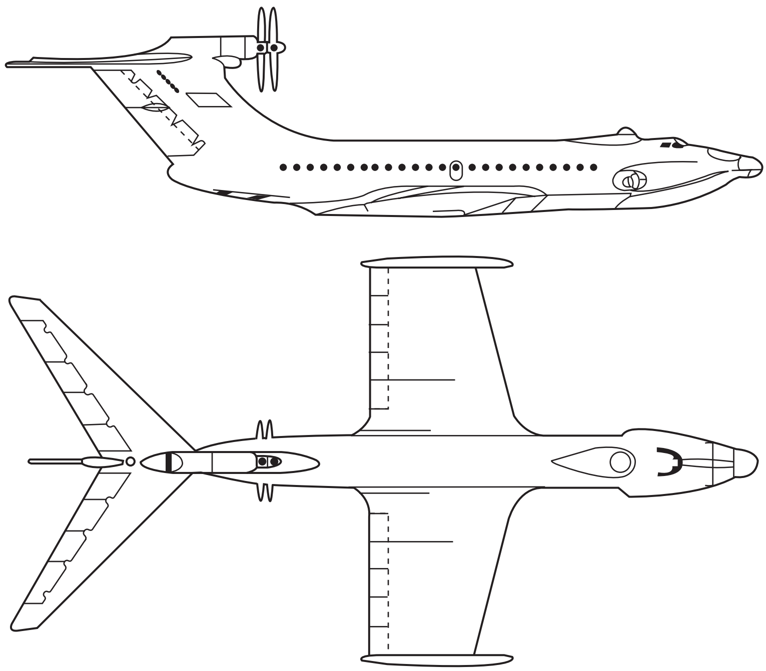


Fig. 2.15 General profile of "Orlyonok"

concluded that these accidents were attributed to Mr. Alexeyev's incorrect design approach. Alexeyev continued to insist that all of the accidents were caused by incorrect pilot handling. Subsequently he was dismissed as the chief designer of WIG and director of the WIG design bureau, and appointed as a head of the test laboratory instead. Mr. Alexeyev died 6 years later in 1980 at the age of 64.

Russian specialists on WIG and high-speed vessels have described to the principal author Prof. Yun that Mr. Alexeyev was indeed a gifted high-speed vessel research engineer and designer and was the founder of Russian hydrofoil craft and Ekranoplan development. He loved and was devoted to the research and design of high-speed vessels and was tenacious in his investigation of the secrets of high-speed marine transport science. He was a great research professional, professor and designer and also an experienced pilot, and a sportsman in high-speed sport on water and on snow. His death was a great loss to Russian WIG craft development (Fig. 2.16).

The enquiry determined that the steel material used for the rear hull and fin structure (steel, grade K482T1) had developed corrosion and fatigue cracking from early on in the trials. Orlyonok was subsequently repaired after redesign to utilise Al–Mg alloy in place of the steel material and several craft built as a series. Structural design of such craft could only be an art at that stage of development, and such engineering art requires operating experience, both positive and negative to move forward.

Fig. 2.16 Photo of Russian WIG pioneer Mr. R.Y. Alexeev

The Orlyonok craft constructed are as follows:

One static test airframe
Orlyonok 01 – S23, 1973, rebuilt and re-designated S-21, 1975–1977
Orlyonok 02 – S25 delivered 1980
Orlyonok 03 – S26 delivered 1983

Following extensive trials with the rebuilt Orlyonok 01, the Russian Navy accepted the craft into marine service on 3 November 1979 as part of the Caspian Sea Fleet based in Kaspiisk on the West Coast. There were plans in the early 1980s to order up to 100 Orlyonok craft, but in 1985 the funds were switched to building nuclear submarines. Operations with the fleet continued after the rebuilding of Orlyonok 01 in 1977 through until October 1993 after which the craft have been static (Fig. 2.17).

Fig. 2.17 Orlynok in formation

The Development of Lun

In parallel with the development programme for the military transport WIG "Orlyonok", the design bureau was also issued an order from the Russian central navy staff to design a naval-guided missile WIG, the "Lun". This craft was to be 400 t all up weight with a payload of up to 100 t.

The design was developed from the Orlyonok basic configuration using eight 13-t thrust NK-87 turbofan engines for bow lift augmentation and two similar turbofan engines at the stern for propulsion in cruising mode once in ground effect. Six ship-to-ship guided missile launchers were mounted on the hull's mid section at an angle of approximately 45° (Fig. 2.18). Leading particulars are listed in the Table 2.3. The craft was constructed between 1983 and 1986. Craft trials were carried out from 1987 to 1989. Lun has travelled about 50,000 km in service and taken off and landed on seas with wave heights of up to 3 m. Figure 2.19 shows a guided missile launch from Lun.

Fig. 2.18 Russian guided missile WIG "Lun"

Fig. 2.19 A guided missile launch from Lun

After the disintegration of the Soviet Union, owing to the lack of budget funding the Russian Navy was not able to continue developing WIG craft. Construction of a second "Lun" was interrupted. However, the accident of nuclear submarine "Comsomoloz" in 1989, with the loss of 42 crew members demonstrated that the Navy needed salvage craft with high-speed capabilities to reach remote accident scenes quickly. They concluded that a WIG would be the best vehicle for such aims. The Alexeyev design bureau was subsequently given an order to design the modifications from the "Lun" to a search and rescue Ekranoplan "Spasatel" for the second hull [5].

Design of this craft was completed in 1991. During its development, tests for salvage operations had been carried out on the existing WIG "Lun". The tests demonstrated that the performance prediction was correct, and the Ekranoplan could shorten the specified rescue operation significantly, compared to alternatives available. Plans for the rebuilding of "Lun" were prepared and the work started. To date the craft has not been completed and put into service.

Key Performance Data for Lun and Spasatel are as follows:

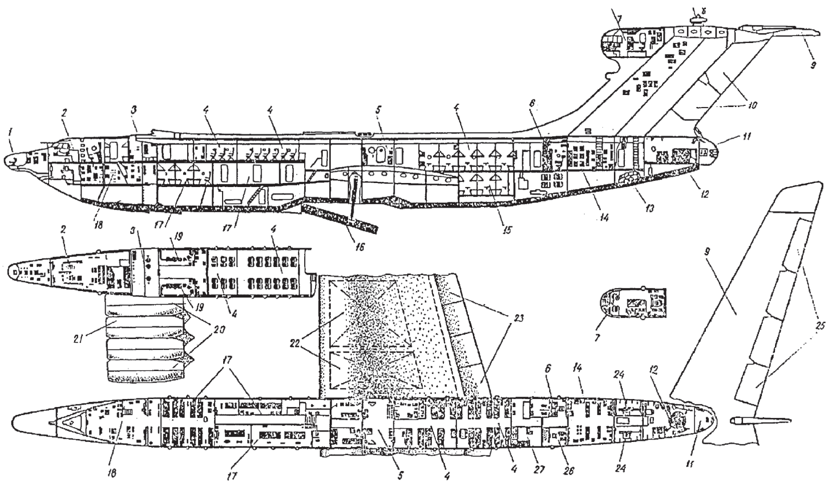
Speed and range:	
Cruising	400–500 kph
Searching	350 kph
Range	3,000 km
Endurance (day and night)	5
Seakeeping quality, SS:	
In flying mode	Unlimited
At take-off/landing	5
Hull borne	6
Accommodation (persons):	
Seats and beds for refugees	70 + 80
Free open area capacity	500
Flying crew and sailors	9 + 19

The aerodynamic configuration of Lun is similar to that of Orlyonok, while its seakeeping is improved because of its larger size. The craft can take off and land in wave heights of up to 3 m.

Figure 2.20 shows the general arrangement of the craft, where

(a) Longitudinal section
(b) Upper deck plan
(c) Plan of observation location on vertical wing
(d) Lower deck plan

(a)



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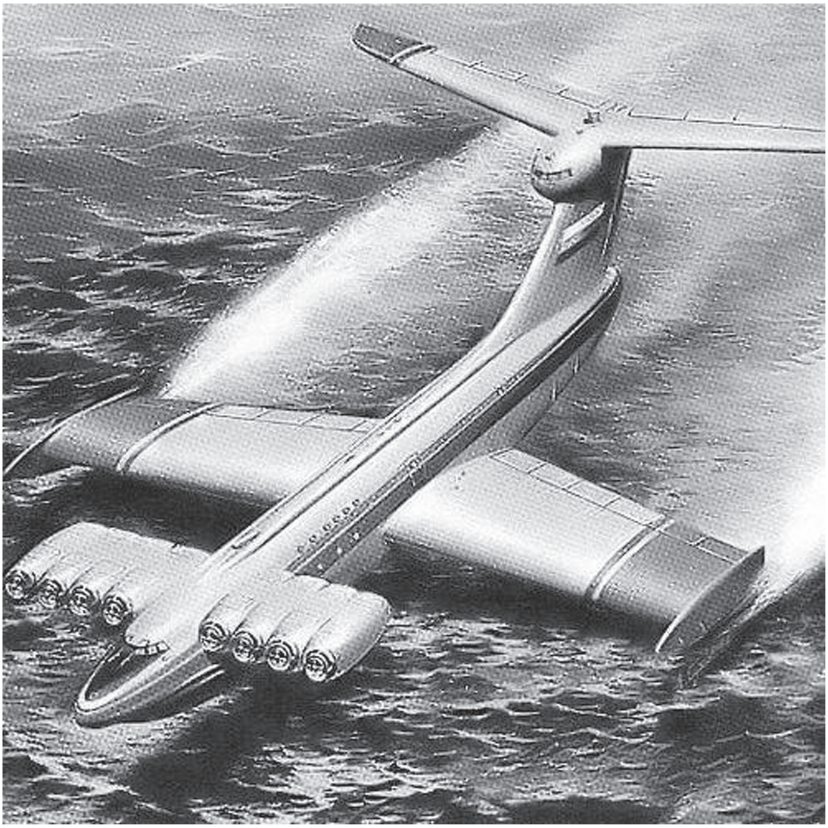


Fig. 2.20 (a) General arrangement of WIG “Spasatel” (b) Artists impression of “Spasatel”

Key to Fig. 2.20

1 Anti-collision surveillance radar
2 Navigation cabin
3 Cabin for engine systems
4 Cabin for refugees
5 Salvage equipment stowage
6 Hawser hold
7 Observation post
8 Radar
9 Elevators
10 Rudder
11 Stern door
12 Cargo hold
13 Container stowage
14 Electrical distribution compartment
15 crew cabin
16 Movable hydro-ski
17 Medicine post
18 main engine start machinery space
19 Auxiliary machinery space
20 NK 87 main engines
21 NK 87 main engines
22 fuel tank
23 Flaps
24 Electrical motor and main engine space
25 Upper rudder
26 Radio cabin
27 Kitchen

Second-Generation WIG

From the mid-1970s, R.Y. Alexeyev led an active research programme to improve the aerodynamic performance of WIG. Wing aerodynamic properties are strongly related to aspect ratio and the relative flying height of the wing above the ground when in ground effect (Fig. 2.21). Alexeyev initially planned to use a high aspect ratio of 5 and form the main configuration as a so-called flying wing (Fig. 2.22) for the second generation, doing away with the rear stabiliser; however, the stability problems with such an aerodynamic arrangement in ground effect were not able to be solved. Eventually he selected an alternative second-generation configuration that combined a main wing of low aspect ratio with additional high aspect ratio outer wings beyond the main wing endplates, and a small high mounted horizontal tailplane for improving trim stability (Fig. 2.23).

The design basis of this PARWIG aerodynamic arrangement is that the bow thruster or turbofan provides pressurised air to the main wing creating a dynamic air

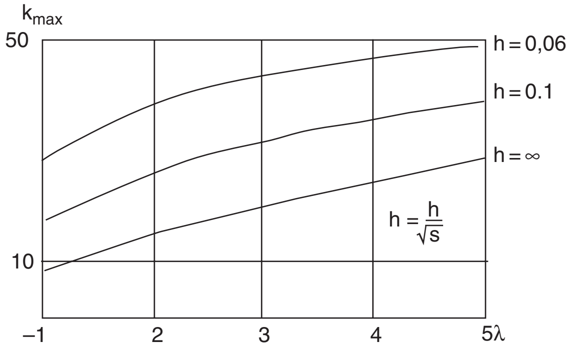


Fig. 2.21 Aerodynamic characteristics versus relative flying height and aspect ratio

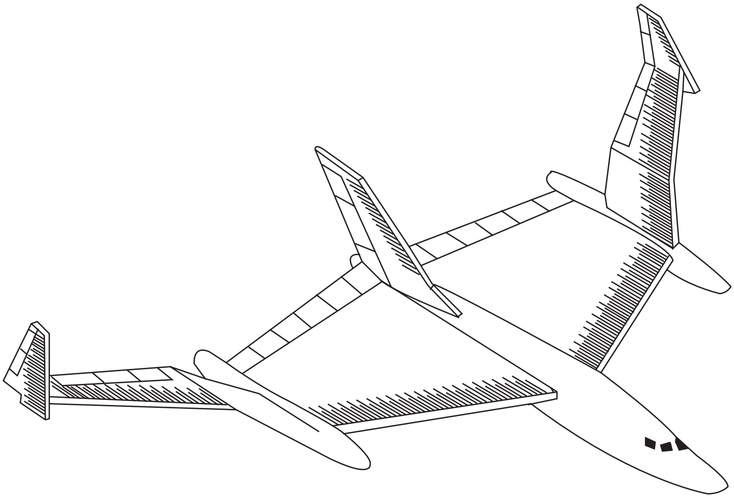


Fig. 2.22 Sketch for WIG with “Composite wing”

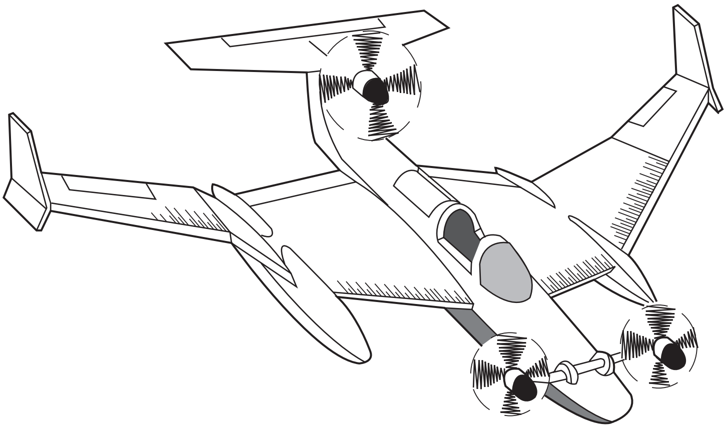


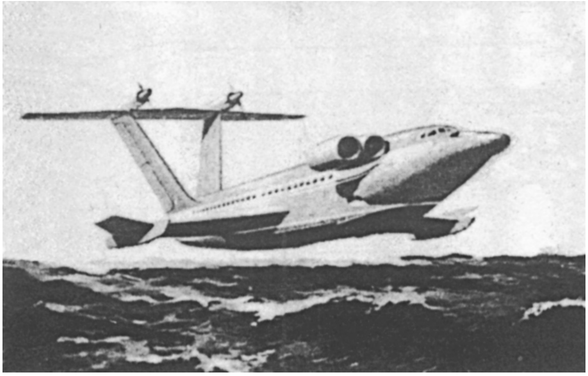
Fig. 2.23 Sketch for WIG with composite wing and small horizontal tail wing

cushion at very low speeds and added lift at trans hump speed to improve the take-off/landing performance. The high aspect ratio side wings provide improved aerodynamic performance at cruise speeds. The improved performance of this composite wing geometry is partly due to the higher aspect ratio of the outer wing, and in addition the outer wing taking advantage of vortex energy at the tips of the main wing.

Figure 2.24 shows an artists impression of the PARWIG configuration Ekranoplan 2 shown also in Fig. 1.17 illustrating the effect of bow-thruster positioning on the main wing.

Figure 2.25 shows the action of the main-wing tip vortex on the side wing (or composite wing). The tip vortex of the main wing induces a vertical upwards airflow V_i in addition to incoming flow velocity V_o. The resultant velocity impinging on the

Fig. 2.24 Second-generation WIG



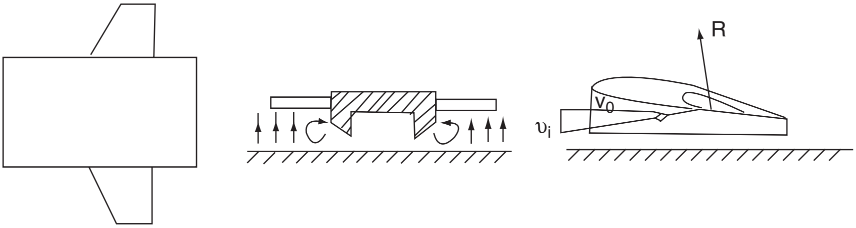


Fig. 2.25 Action of tip vortex of main wing on the side or composite wing

outer wing is increased and angled upwards. The effect is that the outer wing has an increased lift and *L*/*D* ratio, so that they can be smaller than if designed to operate in free air. Winglets are used on many modern jet airliners such as the Boeing 747, and Airbus A300 series to reduce tip vortex intensity and induced drag by interrupting the vortex.

D.N. Sinitsin, the successor of Alexeyev at the design bureau, further developed the second generation of WIG using the composite wing (CK-B) and also added a traditional aviation tailplane to improve stability [6]. Subsequently, his team designed a seagoing 250-seat passenger Ekranoplan with a planned cruise speed of 500 km/h, range 3,000 km, with take-off in 1.5 m significant height seas; and also a larger craft project with 450 seats, maximum speed of 500 km/h, range 6,000 km and take-off in up to 3 m wave height. The aerodynamic efficiency *K* of this craft was projected to be as high as 20.

Table 2.3 shows the potential leading particulars of some Russian second-generation Ekranoplan designs.

Russian WIG specialists concluded from their design studies on these craft that a number of problems concerning WIG aerodynamics needed to be solved before they could become commercially attractive:

(1) Improvements to the main-wing and side-wing aerodynamic characteristics, by selecting a more efficient wing profile for the main wing improve aerodynamic efficiency and craft stability. They projected that the maximum realisable *K*

value should be about 25, by decreasing as far as possible the area of tailplane and fin once the main wing had been optimised. This would improve the payload capacity.

(2) In order to improve craft transport efficiency, one needs to increase the aerodynamic efficiency at high cruising speed. However, a conflict exists between the requirements for the main wing at take-off, landing and cruising operations. The best way to solve these problems is to improve the effect of forward thrusters to increase lift on the main wing at lower speeds and use changing camber of the main wing at different speeds by a form of wing flap.
(3) In order to achieve satisfactory pitch, roll, heave and yaw stability, and at the same time decrease the fin and tailplane area, alternative section profiles to traditional wing sections need to be developed for main and side wings and the airfoils' arrangement optimised in relation to each other. In addition, an automatic control system is really needed for WIG cruise speeds in the 300–500 kph range to improve pitch and yaw control.
(4) A method for assuring course stability and manoeuvrability of the craft in transition operations at maximum lift power is needed. This might be procedural or by use of design attributes. In addition, automating the lift power control system with a programmed interlinked power and thrust direction control may improve craft stability and manoeuvrability during transition between modes.
(5) Development of improved flight dynamics to enable the WIG to fly above the surface effect zone for short periods. The design and operational requirements for craft flying hops and also cruising beyond the surface effect zone were developed from these investigations.
(6) Development of aero-hydrodynamic configuration to ensure safe emergency landing in a seaway from any point of the cruise path (safe ditching performance).
(7) Setting up an international safety code for WIG through the IMO so that maritime nations would have standards to refer to for WIG traffic (this has been done since the mid-1990s).

Second-generation WIG should also ideally be able to operate over water, land, snow or ice surfaces, giving them the ability to operate from unprepared bases, though this may be more important for military than commercial craft [7].

An artist impression of a large passenger and cargo carrying WIG based on these second-generation principles is shown in Fig. 2.26.

Design Studies for Large Commercial Ekranoplan in Russia

Since the first test WIG was constructed by Finnish engineer T. Kaario in 1935, about 70 Ekranoplans have been constructed worldwide, the majority in Russia. However, most of the craft are prototypes and craft built for military application. There are no commercially operated passenger ferries so far and no routes established for passenger transportation.

Fig. 2.26 Large passenger and cargo carrying WIG – FLHRO-PB

WIG designs based on military requirements do not need to be commercially efficient to be successful. Successful commercial WIG craft would need to combine low cost with high transport efficiency, demanding a different type of development programme. WIG terminal requirements will be more like a Hoverport than a ferry terminal, so the initial investment to allow entry into the passenger ferry market may be higher than new designs of fast ferry. All of these factors have restricted the development of Russian WIG. Dynamic air cushion craft are rather different, and fewer of the factors mentioned above resist its development.

Following the approach that larger craft are more efficient, and therefore reduce the unfavourable factors for developing WIG into commercial use, the Russian design houses have proposed to construct a very large seagoing passenger WIG of several thousand tons displacement, with 300 knots cruising speed and a thousand passenger seats in addition to freight capacity.

Such a craft could be operated in the strong surface effect zone, $\bar{h} = 0.05$–0.1, with high aerodynamic efficiency and inherent stability, so reducing the need for complex automatic control systems. Since the high tailplane would be beyond the surface effect zone and its aerodynamic performance would be less efficient, they suggested using a special S profile for the main wing section for improving stability, and reducing or even removing the tailplane. Such very large WIG would be operated on the open ocean. Economy would be satisfactory; however, new challenges would also be presented to research personnel.

It may be observed that the Russian Ekranoplan designs in recent years have generally been developments from the successful Orlyonok basic configuration, to include outer stability wings, etc. This craft configuration, with main-wing form optimised for cruising at 300 kph and faster, requires considerable jet-injected lift assistance for take-off. The performance characteristics are distinctly different below and above take-off and require careful operation of controls while taking off or landing.

Smaller craft have been evolving in Russia over recent years that include much more radical main wing geometries requiring less air cushion assist, and more statically stable while transiting operational modes. This work has paralleled the work in China and Australia during the 1990s.

Volga-2

In the middle of 1970s, Alexeyev realised that due to the complicated equipment, control systems and flying technique necessary for large WIG, it was very difficult to develop such craft as a cost-effective commercial transport at that time. He and his colleagues developed a much smaller and simpler vehicle they named the dynamic air cushion craft (DACC) as an intermediate type between the air cushion vehicle, hydrofoil craft and the Ekranoplan. These craft are designed to be operated in the strong surface effect zone (very close the ground or water surface), so as to obtain good hydrodynamic properties, similar to that of hydrofoils and ACV, but at higher Froude number, two or three times that of ACVs [8, 9].

Volga-2 was the first of this kind of craft designed by the R.Y. Alexeyev High-Speed Marine Craft Design Bureau. The craft could accommodate seven passengers and a pilot, with a maximum take-off weight of 2.7 t, driven by two rotary piston engines rated at 150 hp each as both lift and propulsion engines. The cruising speed of Volga-2 was about 120 km/h with a range of 300 km. The craft handling is simple, more like driving an ACV than flying an aircraft (Fig. 2.27). More detailed leading specifications can be found in Table 2.4 . The craft is characterised by the following:

Fig. 2.27 Dynamic air cushion craft (DACC) type "Volga-2"

(1) It has inherent stability without any automatic control systems as the craft is operated in the strong surface effect zone.
(2) Easy to manufacture, maintain and handle.
(3) Amphibious, and able to boat or cruise over the sea, and hover onto land at low speeds.
(4) Construction of the craft is designed as a boat rather than an aircraft, so is less complex and lower cost.
(5) The craft has a dynamic air cushion under the main wings in normal flight, so vertical slamming acceleration acting on the both main hull and main wing floats will be small. In addition, inflatable bag skirts are installed under the main hull and main wing floats, so its ride is softer to the passengers and gives less fatigue to the hull structure.

Table 2.4 Development series for the Volga and Strizh

	SM-9	SM-10	Volga-2	Strizh	E-Volga-2
Build year	1977	1985	1986	1991	1998–1999
Length (m)	11.14	11.43	11.6	11.4	15
Main wing span (m)	9.85	7.63	7.6	6.6	12.5
Wing area (m^2)					50
Tail wing span (m)					
Tail height (m)	2.57	3.32	3.7	3.6	4.7
Hull breadth (m)	2.0	2.0	2.0	2.0	
Hull height (m)					
Hull draught (m)	0.5	0.6	0.6	0.5	0.45
Aspect ratio, main	0.9	0.9	0.9	3.0	
Tail					
Crew + passengers	1+	1+	1+7	1+1	1+10
AUW (t)	1.75	2.2	2.7	1.63	3.3
Payload (t)	0.5	1.0	1.0	0.5	
Thrust (t)	300 bhp	300 bhp	300 bhp	320 bhp	300 bhp
Engine stern	n/a	n/a	n/a	n/a	
Engine bow	2 off ZMZ-4062-10	2 off ZMZ-4062-10	2 off ZMZ-4062-10	2 off VAS-4133	2 off 3M3-4062.10
Specific power (ps/kg)					11
Take-off speed (kph)	n/a	n/a	n/a	90	
Maximum speed (kph)	140	140	140	175	200
Cruise speed (kph)	120	120	120	150	150
Flying height (m)	0.2	0.2	0.2	0.2 skimming	0.2 skimming
Maximum seastate (m)	0.5	0.5	0.5	0.5 skimming	1.0 t/o and land
Range (km)	n/a	300	500	300	300

Recent Small Craft Designs

Ivolga

Reference [10] details work in Russia to develop a novel WIG named “E-Volga-2” from 1998 to 1999, which can operate over ground as well as water, and in or beyond the surface effect zone (GEZ). The Russian design team call such craft Ekranolet, rather than Ekranoplan, which in Russian suggests that the craft can be flown in free air.

Both the Russian WIG craft Orlyonok and Lun are able to fly in and beyond the GEZ, while Volga-2 can fly only in the strong surface effect zone. The E-Volga-2 combines these attributes in that it can operate on both ground and in or beyond the GEZ. The craft was designed by the “Kometa” Central Scientific Research Institute. Following 1999 the further development of the craft was named Ivolga

Ivolga has a traditional aviation control system including tailplane, fin and rudder, and wing ailerons. Pilots can choose the flying height according to the prevailing conditions. The craft can be operated over waves with height of 1.0–1.5 m. It can traverse holes, ground, swamp and concrete landing aprons.

From Figs. 2.28 and 2.29, one can see the main craft characteristics. The central wing frontal surface is configured in a reverse V shape and with flaps at the rear part of the wing. The side buoys are slender and in catamaran form due to the deep chord of the main wing. They have both longitudinal and transverse steps for good hydrodynamic performance, particularly during take-off. The cabin is located on the centre of the wing arranged higher than the hull or fuselage and with a large window

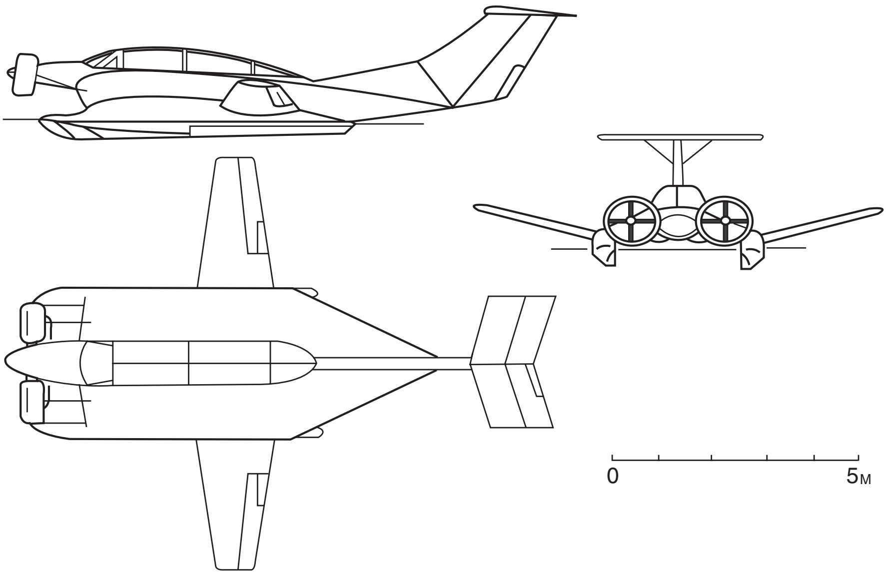


Fig. 2.28 Ivolga general arrangement

Fig. 2.29 Ivolga in flight

area, so that passengers in the cabin will have a good view. The craft also has high aspect ratio foldable composite wings with ailerons located outside the side buoys.

There are two engines located in front of the main wing, which drive a pair of 1.32 m diameter, four blade-ducted air propellers via transmission shafts and universal joints. The propeller shaft is inclined during operation on the ground and before take-off in order to feed the pressurised air into the air tunnels so as to give the craft amphibious ability, short take-off over water and good seakeeping performance. However, at cruising speed the propeller shaft axis is turned to horizontal so as to improve propulsion efficiency. The craft has a T-type tailplane with elevators and rudder. It is planned to be manufactured for both small commercial passenger operations and military applications. Technical data for this craft are as follows:

Maximum take-off weight	3,300 kg
Wing span	12.5 m
Wing area	50 m
Length overall	15 m
Wing load	65 kg/m
Specific power	11 kg/ps
Crew	1
Passenger	8–10
Engines	Two sets 3M3-4062.10
Power	2 × 150
Capacity of fuel tank	2 × 100 l
Maximum speed	200 kph
Cruising speed	120–150 kph
Flying height during skimming	0.1–0.2 m
Draught in hull borne	0.45 m
Seaworthiness	SS 3-4
Maximum size (length beam height)	15 12.5 4.7 m
Maximum size while composite wing retracted	15 4.6 4.7 m

From the figures one can see the ailerons and air bags at the wing tip plates, so the craft is able to operate both in free air (ailerons are needed for banking in free flight) and over ground (cushion with flexible skirts).

Tests of the prototype began in Moscow in September 1998. From January 1999, tests were carried out on Lake Baikal and on the Angara river with the craft based at Irkutsk supported by Verhne-Lenskiy river shipping company as a test for operation of these WIG craft in Eastern Siberia. The first flight in winter conditions in "hovering" mode was executed on Irkutsk reservoir, 16 February 1999. The first flight in a wing-in-ground effect mode in cruise configuration at speed 80–110 km/h occurred on 20 February 1999.

On 20 August 1999, the craft was demonstrated operating from the shore of Lake Baikal over water and wing-in-ground effect flight in cruise configuration. Up to December 1999, the flights were carried out in wing-in-ground effect mode flown by V. V. Kolganov. From December 1999 craft operation was mastered by D.G. Schebliakov, including on 10 December 1999 a flight in wing-in-ground effect mode at heights up to 4-m manoeuvring around a designated course. On 15 December, flight and manoeuvring outside of wing-in-ground effect (more than l5 m) was demonstrated. On 10 February 2000, a flight was executed on lake Baikal and back during which the craft flew above snow, above water (Angara river stays unfrozen beyond 10–12 km from the source at Lake Baikal) and above ice on Baikal in wing-in-ground and aircraft modes. In 14 October 2000 at 3,700 kg weight, the EL-7 performed take-off, wing-in-ground effect flight at height up to 4 m and landing at height of waves more than 1 m, which corresponds to seastate 3.

The power capacity of the BMW S3-8 engines is sufficient for the continuation of wing-in-ground effect flight with failure of one engine. When in wing-in-ground effect, the EL 7 "Ivolga" has much greater aerodynamic efficiency ($K \geq 25$) in comparison with "airplane" modes ($K = 11$–12) at identical take-off weight and fuel capacity. The average fuel consumption when cruising with a variable flight profile including speed, track and height was 25–30 l of petrol Ai-95 on 100 km of a route at take-off weight of 3,700 kg and speed 150–180 km/h, and 75–90 l of petrol Ai-95 on 100 km route in a "airplane" mode.

Amphistar

Figure 2.30 shows the Russian second-generation WIG "Amphistar". Amphistar is a development from Volga-2 [8], which has been commercialised in Russia. A number of these craft are now in operation for passenger taxi services in Russia and in the Caribbean.

Fig. 2.30 Amphistar

Technical Data Summary for Russian WIG Craft

Additional performance data for a selection of Russian WIG and DACC are listed in Tables 2.5 and 2.6 for readers' interest:

Table 2.5 Summary data of Ekranoplans built in Russia

	SM-6	Orlyonok	KM	Spasatel	Volga-2
Type of craft	WIG	PARWIG	WIG	PARWIG	DACC
Mission	Small experimental model of Orlyonok	Transport	Experimental ship Caspian sea monster	Guided missile or/and rescue ship	Passenger boat
Displacement (maximum take-off, t)	26.42	140	544	Up to 400	2.7
Payload:	1.0	10–20	–	Up to 100	0.75
Transport modification (t)		15		45.0	0.75
Passenger modification		150 persons		450 persons	8 persons
Main dimensions, L B H (m)	31 14.8 7.85	58 31.5 16	92.3 37.6 22	73.8 44 19	11.6 7.6 3.7
Aerodynamic configuration (geometric supporting layout)	Aircraft-type layout with trapezium shape wing	As same as left	Aircraft-type layout with straight square wing	Aircraft type with swept formed wing	Aircraft-type layout with rectangular wing
Geometric characteristic of lift wing: *S* (m) AR	73.8 2.81	307.0 3.07	662.5 2.0	500 3.0	44.0 1.0
Power plant:					
Starting, type and power	2 RD9 turbojet engine 2,040 kg thrust for each	2 NK-8-4 k fan-jet engine 10 t thrust each	8 VD-7-NM turbojet engine 11 t thrust each	8 NK-87 turbofan engine 13 t thrust each	2 rotary piston engine 150 hp each driving two propellers
Cruising: type and power	1 AI-20 turboprop engine 4,000 hp	1 NK-12 MK turboprop engine 15,000 hp	2 VD-7KM turbojet engine 11 t thrust each	8 NK-87 turbofan engines 13 t thrust	
Cruising speed, km/h (knots)	290 (157)	370–400 (200–215)	500 (270)	370–400 (200–215)	120
Range, km (n.mile)	800 (432)	1,300 (800) 2,200 (1,180)	2,000 (1,080)	4,000 (2,160)	300 (182)
Wave height *h* 3% (m)					
Take-off/landing	up to 1.0	1.5	5.0	2.5/3.5	0.5
Cruising mode	up to 1.5	no limit	no limit	no limit	0.3

Table 2.5 (continued)

	SM-6	Orlyonok	KM	Spasatel	Volga-2
Type of craft	WIG	PARWIG	WIG	PARWIG	DACC
Starting distance (km)					
On calm water	2.7	2.4–2.8	−6.0	2.4–2.8	1.0
In specification seastate	4.5	4–5		4–5	
Starting time (s)					
On calm water	50	80	130	80	70
In specification seastate	75	150	200	150	50
Touchdown to stop distance (km)					
On calm water	1.2	1.2	3.1	1.2	0.8
In specification seastate	1.8–2.7	1.7	4.5	1.7	1.0
Minimum turning radius at					
V_c,	50	50	100	50	15
R (m)	4,500	2,500	8,000	2,500	500
Rolling angle (degree)	3–5	15	10	15	0
Take-off speed (km/h)	210	220	280	220	80
Jump (permitted or not)	No	Yes	No	Yes	No
Jump attitude (m)		Up to 50		Up to 50	
Base	On unequipped relatively flat coast site or on pontoon platform	On pontoon platform or equipped site with ramp	Afloat or near special pier	Afloat or near special pier	On gently sloping coast with slope angle up to 3°

Some derivative passenger craft designs have been completed in Russia (see Table 2.5); however, high-speed passenger transport routes using WIG have still not been established there at the current time.

WIG Development in China

Chinese Research and development into WIG craft started in the late 1960s. Two types have been developed, the power-augmented wing-in-ground effect craft (PARWIG) and dynamic air cushion wing-in-ground effect craft (DACWIG). The PARWIG was developed by China Shipbuilding Scientific Research Centre (CSSRC), and China Academy of Science and Technology Development WIG Vehicle Development Centre (CASTD), while the DACWIG has been developed by the Marine Design and Research Institute of China (MARIC) in Shanghai.

Table 2.6 Leading particulars of some Russian DACC, Hydrofoils, ACV and catamarans

Craft type	Catamaran	Hydrofoil	Hydrofoil	ACV	SES	DACC	DACWIG	DACWIG	DACWIG
Model	Zalia	Raket	Lastochika	Irbis	Balguzin	Volga-2	Vilyou	Ardan	Vitim
Production condition	Batch production	Batch	Batch	Batch	Batch	Batch	Design	Design	design
Classification	P	P	O	P	M	P	O	O	O
Seats	60	58	70	28	130	8	80	50	50
Power (kW)	1,660	1,660	2,995	2,126	2,735	295	5,000	2,500	1,500
Speed (km/h)	42	60	85	45	50	100	300	270	240
Range (km)	500	500	700	450	600	500	1,500	1,000	500
Transport capability (Pass. km/h)	2,520	3,480	5,950	1,760	6,500	800	34,000	13,500	7,200
Transport efficiency (person. km/kW)	3.85	5.56	3	5	4.55	4.34	5	5.56	5

CSSRC PARWIG Craft

More than 40 small-scale models were built at CSSRC in the late 1960s to investigate the aerodynamic and hydrodynamic properties of WIG, as well as studying longitudinal, transverse and heaving stability. The models were tested out in the wind tunnel of MARIC in Shanghai and also in the towing tank of CSSRC in Wu-Xi.

Successful testing with the small-scale models (both self-propulsion and non-self-propulsion models), together with theoretical investigations led to a series of manned test craft and passenger craft that has been completed since the end of the 1970s [11, 12].

The full-size craft are characterised as follows: The craft can be launched and landed, without outside aid, from a suitable slipway or landing pad. The boarding and disembarkation of passengers, loading and unloading of cargo, and the inspection and maintenance are all carried out on land without the need of special facilities.

The craft are skidded into the water and complete take-off and landing over water. They can fly into the weak surface effect region and can clear obstacles such as small boats. They can stop safely on water when sudden danger or accident occurs. The leading particulars of CSSRC's PARWIG craft are listed in Table 2.7 (Figs. 2.31 and 2.32).

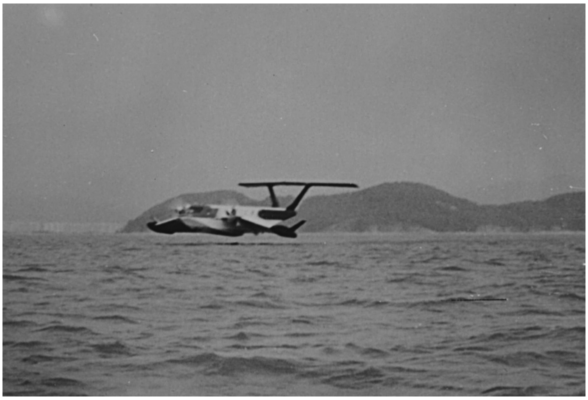


Fig. 2.31 CSSRC's PARWIG type "Sea skimmer 1"

CASTD PARWIG

This craft is designed following floatplane style and was developed by CASTD from 1995, to be used for passenger and goods transportation, tourism, anti-smuggling, patrol and rescue missions. The prototype was designed and constructed between 1995 and 1999. Leading particulars of the craft designated the TY-1 are as follows (Fig. 2.33):

Table 2.7 The leading particulars of CSSRC's PARWIG craft

Type	XTW-1	XTW-IS	XTW-II	XTW-III	XTW-IV	XTW-V	SDJ
Principal	12.60	14.40	18.50	17.90	21.70	29	13.7
dimensions,	8.20	9.80	12.72	12.05	14.50	23.8	11.8
L B H (m)	3.35	3.90	5.14	5.30	5.0	8.5	3.8
Maximum AUW (kg)	950	1,700	3,600	4,000	6,000	25,000	1,900
Crew and passenger	3	5	15	12	20	75	5
Cruising speed V_c (km/h)	100–130	130–150	150–180	144	150	300	130
Flying height at V_c (m)	0.6–1.0	0.5–1.0	1.0–1.5	0.5–2.0	0.0–2.0	1.0–2.0	0–20.0
Seastate for take-off and touch down	6–7 wind force in Tia Lake	SS-3	SS-2	SS-2	SS-2	SS-3	SS-2
Seastate for flying	6–7 wind force in Tia Lake	SS-3	SS-3	SS-3	SS-3	SS-4	SS-3
Maximum range (km)	400	200	900	>400	500	500	250
Engine type	Rotax-447	0–235	IO-540 K	IO-540K185	PT6A-15AG	WS-11	IO-350
Maximum power (ps)	2 × 80	200	2 × 600	2 × 600	2 × 750 kW		2 × 300
Remark	Complete	Complete	Complete	Complete	Complete	Design	Complete

Length overall	16 m
Width overall	11 m
Total height	4.9 m
Take-off weight	4,800 kg
Accommodation	15 persons or 1,125 kg
Engines	Two Lycoming IO-540-K1B5
Propeller	Two variable pitch propellers ducted made of aluminium alloy
Total power	447 kW
Fuel consumption	140 kg/h
Maximum speed	200 km/h
Cruising speed	165 km/h
Flying height	0.6–1.2 m
Seaworthiness	SS 3
Range	400 km

Fig. 2.32 Chinese test PARWIG type "XTW-II"

Fig. 2.33 CASTD TY-1 flying

DACWIG Craft Developed by MARIC

Since the middle of 1960s, MARIC has worked on development of ACV and SES and completed more than 15 different craft designs for civil applications. Due to the disadvantages of speed loss and low seakeeping qualities of ACV, MARIC searched for faster water transport possessing high speed, improved seakeeping and amphibious capabilities for take-off and landing. Model tests of CSSRC PARWIG craft at MARIC facilities encouraged the thought of trying to merge the advantages of ACV and WIG to create a more efficient vehicle. This led to the idea for DACWIG craft. The target was for civil application as a ferry.

Development of the DACWIG was started from the end of the 1970s [13–15]. A series of model tests with more than 30 wind-tunnel models were carried out in MARIC's wind tunnel with emphasis on the investigation of overall configuration, main-wing air-tunnel dimensions and the relationship between the jet-stream sources (bow thrusters) and air tunnel.

The overall configuration remained a simple low aspect ratio rectangular main lifting wing, no anhedral or taper, and side buoys shaped to efficiently contain a dynamic air cushion aimed at being able to hover statically.

The wind-tunnel models were succeeded by free flying radio-controlled model tests at the beginning of the 1980s and a manned test craft (type 750) that was completed in the middle of the decade, Fig. 2.34.

Fig. 2.34 MARIC's test DACWIG type "750"

The leading particulars of the type 750 are as follows:

Take-off weight (AUW)	745 kg
Payload	172 kg
Length overall	8.47 m
Span	4.8 m
Height	2.43 m
Cruising speed	132 km/h
Maximum flying height	0.5 m
Range	130 km
Maximum deceleration, emergency stop	1.54 g

Take-off performance: The craft can take off in 0.5–0.7 m wave height with 4–5 Beaufort wind scale and gusts to Beaufort 6 over the lake. Acceleration to take-off is about 30 s, equivalent to 160 m at 45 km/h.

Seakeeping quality: The 750 has flown in 0.5- to 0.7-m seas in Jin-Sa lake. The limited space has meant that there is no sheltered spot to take-off and fly into higher seas. It can be turned at flying speed and running at different wind and wave direction with 0.3° of average pitch angle, 0.52° of average roll angle.

Amphibious ability: The craft can take off from ground and run onto water and vice-versa and also fly over uneven as well as unprepared ground.

Manoeuvrability: The craft can be turned at low speed and rotate itself while hovering almost static and can fly in a zigzag course. The circling time at high speed was about 2.5 min, with 600-m turning radius.

Hull material: The craft is built entirely in GRP.

The trials of the 750 were completed at the end of the 1980s. Since then, MARIC started to develop a passenger DACWIG called the SWAN in the 1990s [16]. The features of "SWAN" (Fig. 2.35) are as follows:

- Operation in strong surface effect zone, with safe and easy handling and maintenance.
- Credible and reasonable construction cost.
- The craft is able to land on its air cushion and traverse slopes of 5° gradient and manoeuvre both on ground and water. It operates from a slipway rather than moored to a pier.
- The craft is able to operate hull borne, air cushion borne (0–80 km/h) and flying at speeds of 80–130 km/h at flying height of up to 1.0 m, within a range of 300 km.
- Maximum take-off weight 7.2 t, including up to 20 passengers.
- The craft can take off and touch down safely in seastate 2–3.

Duralumin-type LY12 is used for the main hull structure, and CIBA honeycomb composite material for other parts, such as side buoys, main wing, tailplane and fin.

Fig. 2.35 Chinese passenger DACWIG type "SWAN"

Three aviation-type piston engines are installed, two HS6E-1 engines for lift driving bow-ducted four-blade air propellers and an HS6A engine for propulsion driving a two-blade controllable pitch-free propeller.

Model tests in MARIC's wind-tunnel laboratory and static hovering tests over a solid screen were carried out in MARIC from 1995. In order to save financial budget, MARIC were obliged to use relatively small experimental models with scale ratio $\lambda = 11.5$–13. More than 10 half models were tested in the wind-tunnel laboratory. Following the successful experiments on the half models, normal wind-tunnel tests with full models, free flying tests in wind-tunnel facility and static hovering tests for the whole model were carried out successively, prior to work starting on the full-scale craft (Fig. 6.9).

After the model tests had demonstrated satisfactory aerodynamic parameters for static lift/thrust ratio, aerodynamic properties, aerodynamic balance, stability, etc., a self-propulsion radio-controlled model test and towing tank test were carried out to validate its stable operation on practical water surface condition, and craft drag over water before and after take-off. Based on the results of these experiments, MARIC started re-design and construction in 1997. Operational trials were begun in 1998. Figure 2.36 shows the general arrangement of "SWAN" (after conversion as detailed below), with numbered keys as follows:

(1) Forward mounted ducted air propeller
(2) Guide vane
(3) Air propeller for propulsion
(4) Horizontal tail stabiliser and rudder
(5) Tail fin and rudder
(6) Composite wing
(7) Lift engine
(8) Propulsion engine
(9) Flap
(10) Forward and rear passenger cabin
(11) Navigation cabin
(12) Power transmission system for forward lift engine
(13) Main wing
(14) Side buoy (sidewall)
(15) Main hull

The main functions can be explained as follows:

- The forward-mounted ducted air propeller and lift engine (1,7) are used for blowing air into the air channel and create an air cushion for static hovering over ground, and take-off over water, in addition, providing thrust for the craft for take-off and cruising flight.
- The guide vanes (2) are used to adjust the direction of the ducted air propeller air jet to adjust the centre of lift as it moves forward at increasing speed.
- The propulsion air propeller (3) and propulsion engine are used for additional thrust for take-off and cruising flight.
- Tailplane and elevators (4) are used for maintaining stable dynamic flight trim.
- Fin and rudder (5) are used for course stability and manoeuvring.

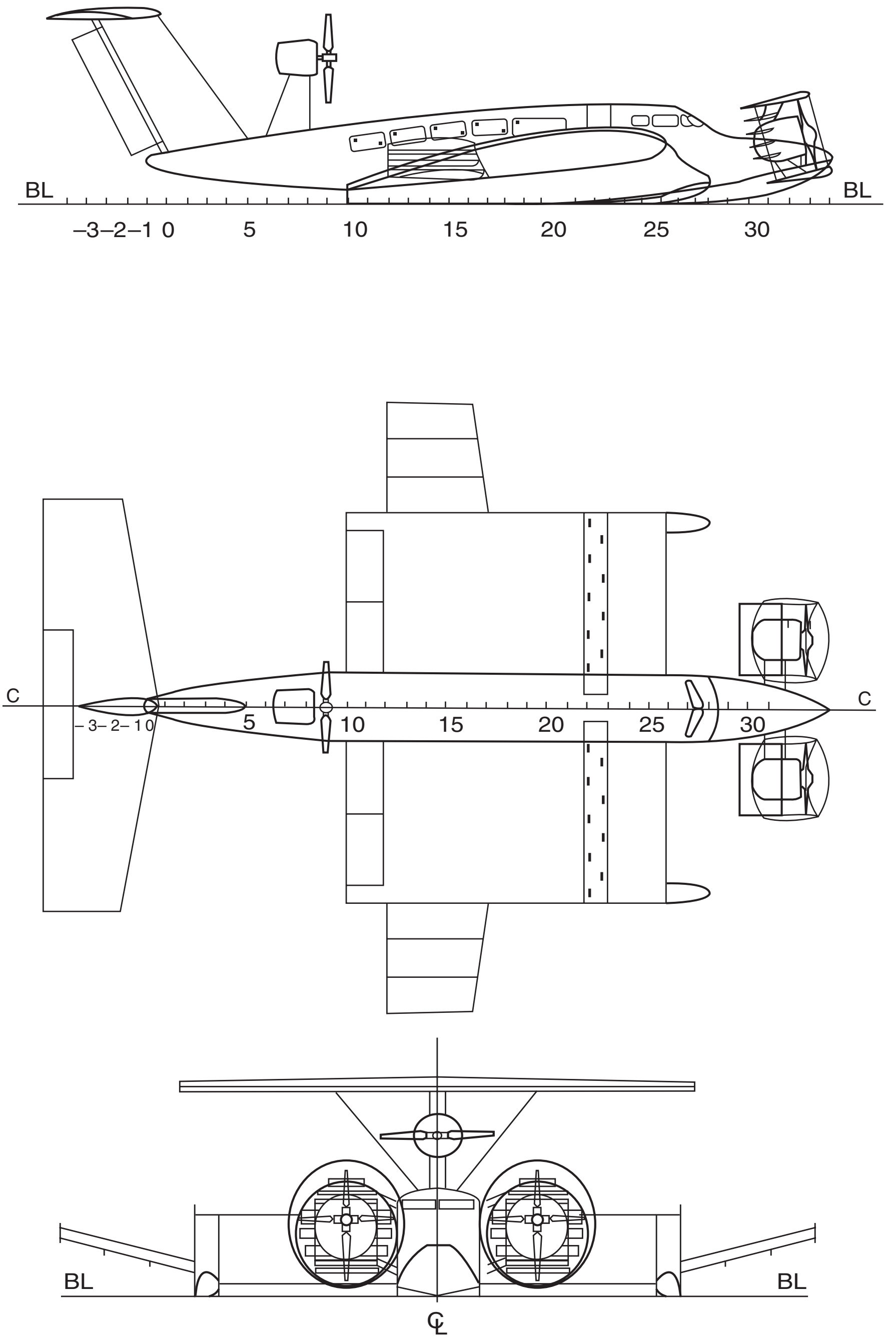


Fig. 2.36 Swan general arrangement

- Composite wing (6) is used for providing part of aerodynamic lift and, at the same time, for the adjustment to centre of lift for stable cruising flight.
- Flaps (9) are used as the sealing device for the air cushion and for the centre of lift adjustment, as well as adjusting the static trim of the craft in flight.
- In the forward and rear passenger cabins (10), there are 12 fixed and 6 additional seats for passengers.
- There are two seats for pilots and two additional seats in the navigation cabin (11).
- The power transmission system from the lift engine (12) to the ducted adjustable pitch air propeller comprises floating shafts and constant velocity joints.
- Main wing (13) provides the main aerodynamic lift;
- The side buoys (14) provide static buoyancy in hull-borne mode, air cushion sealing in cushion-borne mode, and act as aerodynamic endplates to the main wing in flying mode.
- Main hull (15) provides buoyancy when afloat and passenger accommodation. It also is the main structural element of the craft supporting the main wings and tailplane.
- A thin keel (16) at the stern is used to improve the course stability when hull and cushion borne at slow speed over water.

All the control surfaces, such as guide vanes, flaps and elevators, are driven by a hydraulic system, except the rudder.

The craft was designed by MARIC′ and constructed by Shanghai Qiu Xin Shipyard [17]. Construction of "SWAN" was completed in 1997, and initial testing carried out in the same year. The leading particulars are as follows:

Length, width, height overall	19.04, 13.4, 5.2 m
Weight overall	7,300–8,000 kg
Passengers	15–20
Engine model and number	HS6E × 1, HS6A × 2
Lift power	2 × 257 kW
Total power	724 kW
Speed	130+ km/h
Froude number at cruise speed	8.28

The craft carried out test and development trials between 1999 and 2002 in its original configuration. Operations of "SWAN" verified that the design objectives of the craft were achieved, such as good static hovering performance, overload ability of the craft during both static hovering and take-off, and fine speed performance. Tests of the craft have verified the following characteristics:

- High static lift thrust ratio and amphibious capability. The craft can be landed and launched as well as manoeuvred on a very small landing site along the Din Sah lake outside Shanghai.

- Low hump drag during take-off and maximum speed in excess of design specification.
- Satisfactory stability in the various operational modes.

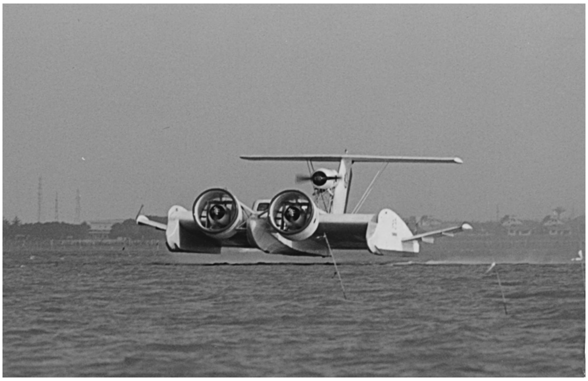
The Conversion of "SWAN"

The initial trials programme showed that the long power transmission shaft to the bow engines was unreliable. In addition some of the engine auxiliary transmission components proved unreliable due to using radial-type aviation piston engines. The craft has therefore been converted from the long shaft transmission for the bow engines to a "composite air propeller-duct" system where the engine is put into the air duct and drives the air propeller directly, so as to eliminate the long transmission shaft. The engine-cooling conditions, vibration level and transmission reliability are all improved significantly.

However, since the width of the engines is large due to the radial arrangement of the cylinders, the blockage of airflow in the duct is serious and the aerodynamic force balance of the craft as well as longitudinal stability in flying mode of the craft became complicated.

After some redesign of the craft, using enlarged composite wings with significant dihedral angle and wing fences, as well as an enlarged tailplane, and redesign of both air duct and guide vanes at the bow-thruster duct-trailing edge, tests of the converted craft showed that static hovering characteristics, speed performance and stability were improved. Figure 2.37 shows the converted "SWAN" in flight.

Fig. 2.37 Swan mark 2



MARIC has planned to develop a fully commercial DACWIG based on the Swan, enlarged to 80–100 seats, with a service speed of 125 knots for application as a passenger ferry. Such a craft could be operated on Tai Wen Strait, Bo Hai Bay, Yellow sea and around the Hong Kong district. It is in the initial design stage. An outline is shown in Fig. 2.38.

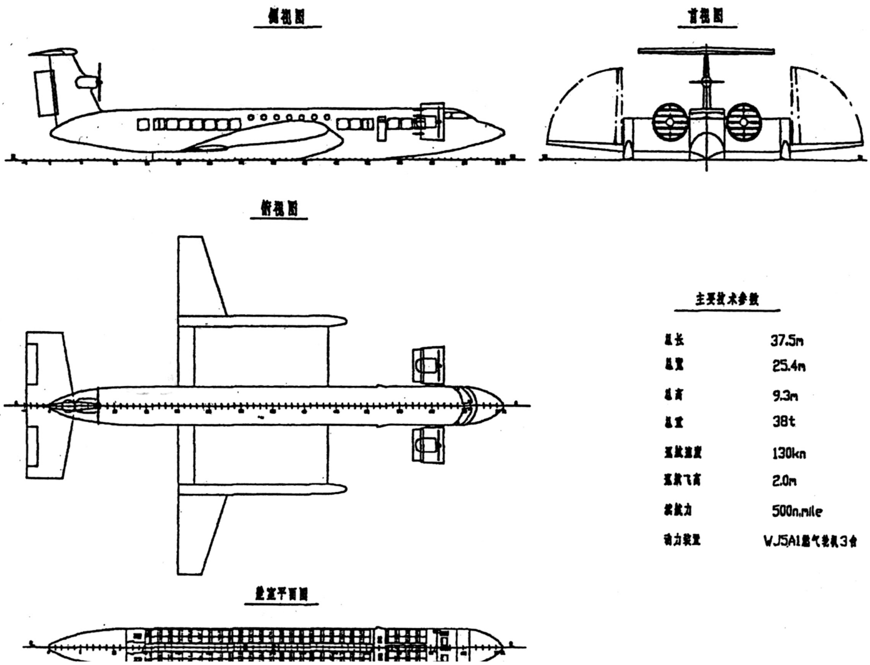


Fig. 2.38 Commercial development of Swan – 100-passenger craft

Leading particulars of the proposed craft are as follows:

Maximum length	34.00 m
Maximum width	23.50 m
Maximum height	9.30 m
Cruising speed	125 knots
Cruising flying height	2 m
Maximum flying height	2.5–3 m
Range	500 n.mile
Passengers	80–100
Total weight	35 t

Machinery:	Two gas turbines, model WJ5A1 rated at 1,750 kW, driving two ducted air propellers for lift and propulsion at bow and one WJ5A1 rated at 1,750 kW for cruise propulsion
Seakeeping:	The craft can take off and fly in seastate 4–5.
Manoeuvrability:	Can turn about its own CG and move in a zigzag in high speed flying mode.
Amphibious:	The craft can be landed and launched into water on cushion and operate over grass land, swamp and ground covered with snow.

WIG Developments in Germany

Tandem Airfoil Flairboats (TAF)

Dr. G.W. Jörg of Germany developed WIG designs based on his experience as a pilot of nearly 20 years during the 1970s and 1980s. Dr. Jörg's view is that if ground effect is to be used for a new transport system, especially to adapt better to shipping and harbour traffic, one should not base the system on the idea of an airplane flying in ground effect [18]. His concepts have been aimed at marine craft operating in the strong ground effect zone, with a small clearance relative to wing chord length.

The concepts developed by Dr. Jörg, began with a single negative delta wing form to encourage ram air cushion underneath the wing. Several models were built to investigate aerodynamic performance. The single ram-air wing in Jörg's early experiments was later replaced by two identical parallel wings in a tandem arrangement. The basis for this change was as follows:

- Higher efficiency of the wings was achieved.
- Stability improved, since both wings are moving in the same medium (strong ground effect).
- Tandem wings allowed an elongated hull configuration so total resistance was reduced.

The wings were linked by two endplates and these formed a kind of stream line channel for airflow. This resulted in better usage of ground effect and an increased static stability of the craft in motion over the sea (rough sea) and during landing in wave conditions.

The engine and air propeller was configured at the stern mounted on the fin with the following characteristics in mind:

- Better steering and resistance to side-winds by using a blown rudder
- Safety for motor and air propeller against wave impacts and in-harbour manoeuvring by placing them at the stern of the craft
- Higher efficiency forward thrust
- Usage of the "Coanda Effect" on the rear wing by induced velocity from the propeller
- Less water spray at take-off

For the Tandem front and rear wings, new computer-optimised ground effect profiles were developed. The improved stability by mutual positive influence was verified in wind-tunnel tests.

It is interesting that the initial problem experienced with the SM-1 in Russia was overcome by Jörg, principally by optimising the airfoil, designing for lower speed and connecting the two airfoils with a single side buoy! After several years development of this type of craft, the German Ministry of Transport surveyed and approved the Tandem Airfoil Flair Boat as a boat or ship.

- IMO Annex 8 forms a basis in the International Standards Part 1, Definitions.
- IMO has classified the TAF equally in 1994 in "Group A", i.e. according to motorboat and motor ship regulations.

Figure 2.39 shows the main configuration of the TAF VIII-3 and Fig. 2.40 shows the TAF VIII-5 craft, both prototypes employed for testing, while Fig. 2.41 shows an impression of the TAFVIII-7, a proposed passenger ferry craft. Table 2.8 shows the leading particulars of TAF series.

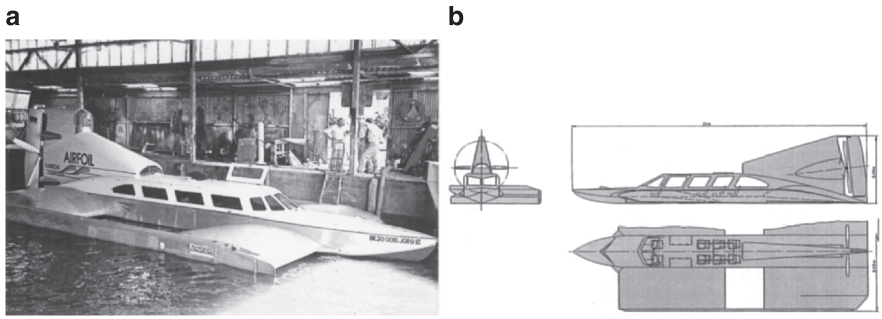


Fig. 2.39 TAF VIII-3 (**a**) photo; (**b**) diagram

Lippisch

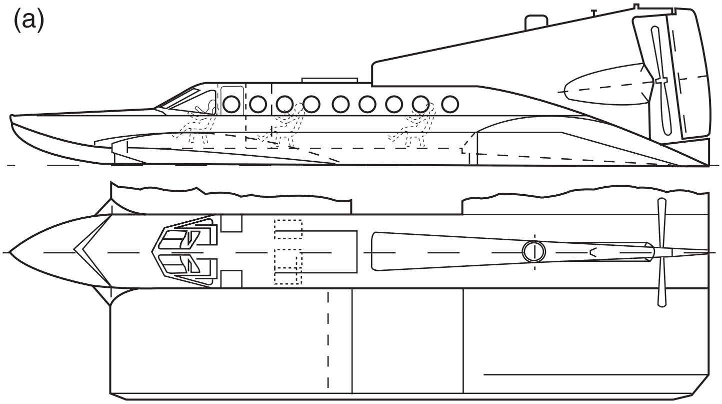
At the beginning of the 1960s, Dr. Alexander Lippisch in Germany developed an alternative WIG configuration to the low aspect ratio rectangular wing configuration of Alexeyev in Russia. The configuration was characterised by the negative dihedral (anhedral) Delta Wing and three control surfaces (rudder, elevators and ailerons), similar to an aeroplane. The concept has no lift augmentation for take-off.

The X-113 single-seat test craft was designed by Lippisch and built under a contract with the German Ministry of defence by RFB, a company within the VFW/Fokker Aircraft group of Germany and Holland, in 1970. The craft configuration, Fig. 1.13, comprises a fuselage with stepped planing lower surfaces, main wings with significant anhedral and tapered chord so as to create a triangular dynamic air cushion space. Planing floats were mounted on the main wing tips and outer winglets with approximately 60° dihedral for roll stability. Propulsion was provided by a single two-cylinder Nelson engine of 48 bhp (38 kW) driving a two-blade open wood propeller mounted on a pylon above the main wing.

Table 2.8 Leading particulars of the TAF series WIG

Type of craft	TAF VIII-1	TAF VIII-2	TAF VIII-3	TAF VIII-4	TAF VIII-7
L B H (overall) (m)	8.30	11	14.0	18	45.6
	3.40	4.75	5.85	7.19	16.6
	2.00	2.35	3.30	4.05	9.00
Overall weight (t)	0.75	1.60	3.15	4.60	60
Maximum useful load (t)	0.20	0.40	0.80	1.20	14.0
Crew and passengers	1	1	1	1	2
	1	3	7	11	133
Engine power (HP)	100	238–300 Porsche M 44 3.0 L	550 Porsche 5.8 L	750 Marine Power 7.8 L	2 × 5,600
Cruising speed (km/h)	125–135	140–155	145–160	160–170	185–210
Cruising level (m)	0.25	0.30	0.42	0.53	1.25
Remark	Completed	Completed	Completed	Completed	Design

(a)



(b)

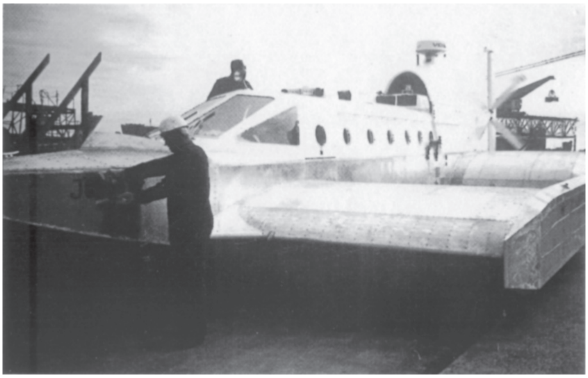
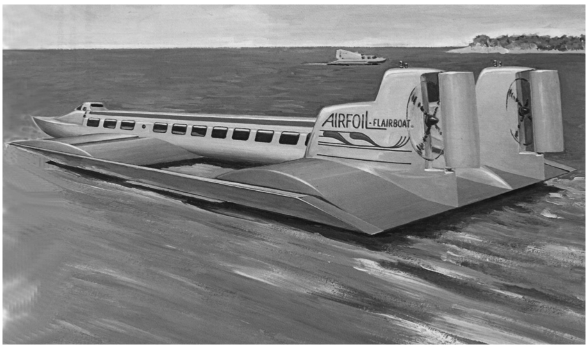


Fig. 2.40 TAF VIII-5 (**a**) external profile; (**b**) photo

Fig. 2.41 TAF commercial craft artists impression



The complete structure was built in composite materials, resulting in a very light weight for its dimensions, of 250 kg. It was able to fly in ground effect and also as a light aircraft up to 800 m (accompanied by a Bell Huey helicopter escort!) in trials during 1971 and 1972.

The success of X-113 led the German Ministry of Defence to support a follow-up development of a six-seat craft, the X-114 in 1977 (Fig. 2.42), as a prototype for coastal patrol duties. This craft, also built in composites, was powered by a 200 bhp. Lycoming light aircraft motor driving a 1.2-m diameter ducted fan mounted behind the passenger cabin above the wing. The X-114 retained the cranked single fin and high mounted tailplane and elevators of X-113. The wing tip side buoys were enlarged and extended further forward of the main-wing leading edge so as to provide the main buoyancy while afloat. The fuselage remained above water level while floating.

Fig. 2.42 X-114

X-114 had a retractable undercarriage so that it could drive up a launch ramp. During the development programme, the undercarriage was replaced by a set of retractable hydrofoils specially designed by Supramar of Switzerland. These were intended to shorten the take-off run for the craft by reducing drag, but created the opposite effect. The hydrofoils raised the side hulls clear of the water at lower speed, while at the same time lifting the main wing further away from the surface, reducing the ground effect. The craft then had to accelerate to a higher speed before take-off could occur. Up to 145 kph, the hydrofoils produced the lift without any other critical input. In an experiment, the pilot was requested to make water contact with foils lowered, at 150 kph. Unfortunately the foils touched the water at a negative pitch angle and subsequently pulled the craft into the water and destroyed it. The pilot was recovered safely.

Apart from the negative results with hydrofoils, the remainder of the X-114 trials were very successful, meeting all the Ministry of Defence objectives.

Following X-113 and X-114, RFB continued its developments with a number of different designs including the X-117 taxi and 15 seats, and 32 seat passenger ferry designs. In 1997 the Fokker aircraft group went into liquidation, and the complete design database together with the X-113 prototype was purchased by Flightship of Australia (leading particulars are given in Table 2.9).

Table 2.9 Leading Particulars X-113 and X-114

Geometry	X-113	X-114
Length (m)	8.43	12.83
Wingspan (m)	5.89	8.77
Height (m)	2.0	2.92
Weights		
Empty (kg)	250	1,040
Fuel (kg)	11	80
Payload (kg)	99	380
Maximum take-off weight (kg)	360	1,500
Payload fraction	0.275	0.253
Propulsion		
Engine	Nelson H63-CP	Lycoming IO-360
Type	Air-cooled 2 cylinder	Air-cooled 4 cylinder
Power (kW)	36	180
(bhp)	48	240
Propeller	Two-bladed wooden open propeller	Three-blade 1.2-m ducted variable pitch
Performance		
Take-off speed (kph)	40	100
Cruise speed (kph)	80	150

Hoverwing

Mr. Hanne Fischer was a technical director of RFB through the period of the X-113 and X-114 WIG developments and played an important part in its success. After retiring from RFB, Mr. Fischer founded the company Fischer-Flugmekanik (FF) together with his partner, Klaus Matjasic, their target being to develop ground effect technology towards commercial application [19]. Two prototypes, the AF1 and AF2, were built and tested and a production design developed, the AF-3, as a two-seat recreational craft. Production rights to the design were sold to RFB who subsequently built the production prototype designated AF3-A in 1990. The three craft are shown in Fig. 2.43a, b, c.

AF3 is an IMO type B WIG (capable of hops only, rather than free flight), a little larger than X-113, powered by a BMW 90-hp motorcycle engine driving a six-bladed 1.1-m ducted fan. While designed with folding outer wings, it is still too large to be towed on a trailer like a small boat and would require a permanent operational base and so was not able to be successfully marketed for recreational use in Europe. The craft was included in the package purchased by Flightship. Key data are shown in Table 2.10 .

FF turned their attention to the development of passenger ferry type WIG under the name Hoverwing. Their initial work was government sponsored by the German Ministry BMB+F. FF considered that a high-speed SES, utilising an air cushion between its catamaran floats and flexible sealing at the bow and stern

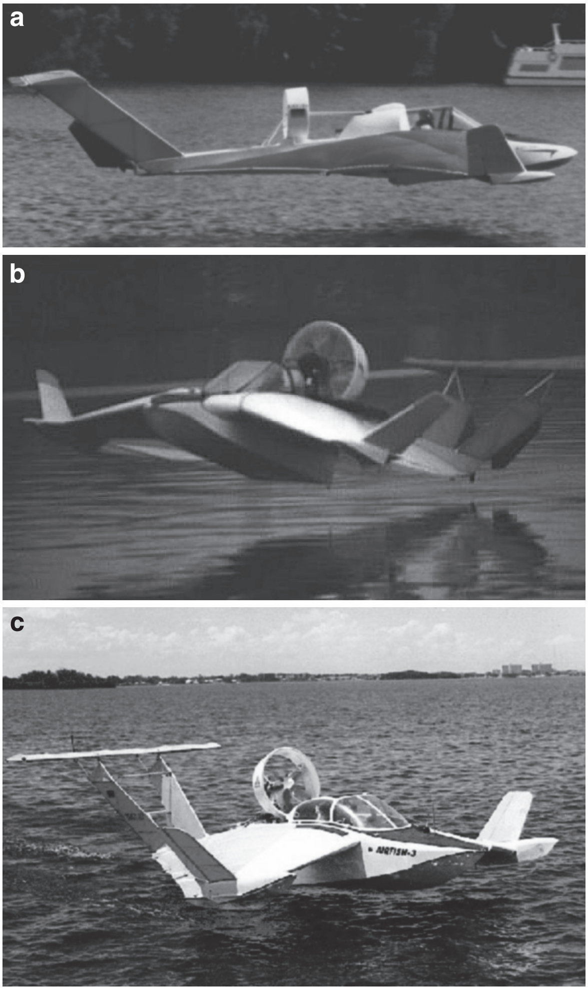


Fig. 2.43 Airfish: (**a**) AF-1, (**b**) AF-2 and (**c**) AF-3

of the vessel, was already technically advancing into the area of WIG take-off speeds. In order to utilise this advantage for the take-off phase of a WIG, FF developed a concept in which the catamaran float design is comparable with the SES, but in which the supply of the air cushion is achieved by using a small part of the propeller slipstream. Figure 2.44 explains the working principle of the Hoverwing.

FF has prepared a design, the “Hoverwing 80”, with the target to transport 80 passengers at 100 knots. A prototype scale test craft at 1:3.35 scale designated the Hoverwing 2 VT has been completed. Figure 2.45 shows the craft operating on the Baltic Sea.

The leading particulars of Hoverwing 2 VT are as follows:

Table 2.10 Leading particulars Airfish 3-A

Geometry	AF3-A
Length (m)	9.9
Wingspan (m)	8.6
Height (m)	2.6
Weights	
Empty (kg)	540
Fuel (kg)	32
Payload (kg)	128
Maximum take-off weight 0.3-m waves, light wind (kg)	700
Payload fraction	0.182
Propulsion	
Engine	BMW 1200
Type	Air-cooled 2 cylinder, 4 str
Power (kW)	67 @ 7,500 rpm
(bhp)	90
Propeller	Six-blade, 1.1-m ducted fan
Performance	
Take-off speed (kph)	40
Cruise speed (kph)	120

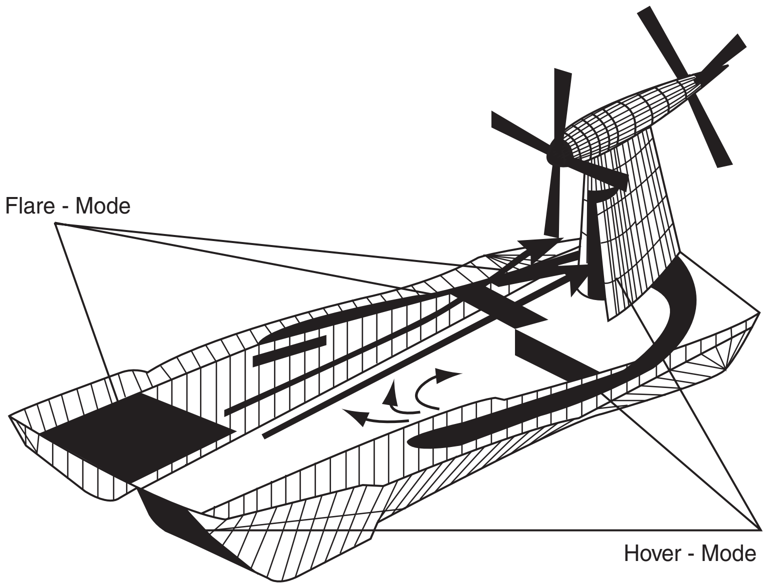


Fig. 2.44 Hoverwing design principle showing low and high speed configurations

Fig. 2.45 Hoverwing 80 flying in the Baltic Sea

Length overall	9.87 m
Width overall	7.73 m
Height overall	2.93 m
Weight	812 kg
Speed	120 km/h
Cruising flying height	20–40 cm

WIG in the United States

During the 1960s and 1970s, the model tests of a number of configurations of ground effect machines were carried out under defence development programmes to look at fast marine vehicles. While theoretical papers and some artist impressions of futuristic craft were published, for example Fig. 2.46, the development focus remained with high-speed SES until the mid-1970s and subsequently with hovercraft for amphibious assault. The US Navy did sponsor a number of research programmes into ram air winged craft, including analytical and model testing, for example the programme outlined by Gallington in Chapter 5 [3].

This work was mainly carried out in parallel to the research on ACVs, as part of the search towards the “100 knot Navy”. In the early 1970s, the choice was made to develop large high-speed SES rather than other concepts. Subsequently this programme was cut short by the mid-east fuel crisis and the US Navy attention switched to other programmes such as the nuclear-powered submarine.

More recently, in the mid-1990s, a company named Wingships Inc. has performed conceptual studies for a hybrid Ekranoplan concept for the commercial market. The design, known as the Hoverplane, is a combination of existing WIG and conventional hovercraft technologies, see [20].

The main body of the vessel is designed as a shallow catamaran or tunnel hull, which is then sealed with semi-rigid skirts forward and aft. By pumping air into

Fig. 2.46 Artists impression of futuristic US flying machine

the resulting chamber, the vessel is able to manoeuvre on the water as a surface effect ship. As the forward motion of the craft increases, the pressure in front of the forward skirt overcomes the internal pressure behind it and the incoming air provides the support lift under the tunnel hull of the craft. The craft then operates for a short transitional period in this mode allowing all the engine power to be applied to forward thrust, further accelerating the craft to its take-off velocity.

Under current US regulations, WIG craft would be classified as boats requiring USCG certification, and not required to pass Federal Aviation Authority certification. The leading particulars of some Wingship Hoverplane design proposals are listed in Table 2.11 .

Table 2.11 Leading particulars of some Hoverplanes proposed by Wingships Inc. of the United States

Type of craft	HP-7	HP-16	HP-20	HP-60
Length overall (ft)	35	60	75	120
Wingspan overall (ft)	25	40	50	80
Seats	7	16	20	60
Flight elevation (ft)	3–5	5–8	6–10	10–16
Weight (lbs)				
-Empty	2,180	5,460	7,500	20,700
-Payload	1,500	3,640	5,000	13,800
-Gross	3,680	9,100	12,500	3,45,000
Power (hp)	300	2,250	2,300	2,600
Range (miles)	400	500	600	700
Fuel capacity (US gals)	50	100	200	300
Performance (mph)				
-Take-off speed	50	55	60	65
-Cruise speed	90	100	110	130
-Maximum speed	120	150	160	170

Separately to the large commercial venture proposals, in the United States during the last decade, a number of enthusiasts have begun to construct WIG craft for their own use. The first successful design has been that of Bob Windt, a pioneer also in ACV design. The Universal Hovercraft WIG is a modified UH-18P hovercraft design with a pair of simple fabric wings and an extended tail including a tailplane and elevator, Fig. 2.47. The craft flies in a steady manner in calm and near calm conditions. Take-off is at about 60 kph and the craft cruises at 90–100 kph. The cushion system is integrated with the propeller drive and so runs permanently. Since the wings are assembled on site, the craft can be trailed in the normal way, as a hovercraft. The craft has no main wing flaps, so flight altitude is controlled simply by engine power and elevator position.

Fig. 2.47 Universal Hovercraft UH-18P-WIG

The Weber brothers have also designed their own WIG employing a tandem wing configuration, Fig. 2.48, and a number of other enthusiasts are designing and building craft after being encouraged by the success of the UH18-P WIG.

WIG in Australia

Sea Wing

Hobart-based Sea Wing International has prepared design proposals for a WIG series named Sea Wing [21]. The design is based on the reverse delta main wing configuration and ram-air lift. Ducted propulsors are mounted above the wing. A retractable undercarriage with brakes and steering is incorporated for independent taxi, slipping and beaching which, allows for a reduced ground handling and maintenance infrastructure.

The Sea Wing range is proposed to be powered by twin diesel engines ranging in size from 80 to 350 kW each. These drive two overhead ducted fans giving a take-off run, again depending on the vessel size, of between 80 and 100 m on water, with

Fig. 2.48 Weber WIG craft

separation taking place at about 35–45 knots. Landing is achieved by decelerating over water, giving a run-out of 40–70 m. The larger craft proposed also include a water jet propulsion system to aid acceleration through to take-off.

Altitude is controlled exclusively by forward speed; automatic pitch stability prevents undue alteration to the angle of attack of the wing at any time. This aims to ensure a stall proof aerodynamic attitude on all points of the craft's performance envelope. The Sea Wing 02 vessels are proposed to operate in up to Force 6 (25 knots) wind speed, which equates to safe, high-speed travel over 2.5 m waves with take-off and landing in waves of up to 1.5 m (on page 90). The leading particulars of Sea Wing WIG are listed in Table 2.12 .

Table 2.12 Leading particulars of Sea Wing WIG craft designs

Craft type	Sea Wing 02	Sea Wing 05	Sea Wing 12
Length overall (m)	11	16.7	25.3
Width overall (m)	10.0	16.4	24.0
Height overall (m)	3.0	4.6	6.0
Draught-loaded (m)	0.4	0.6	0.9
Weights (kg), empty	1,400	3,000	6,500
payload	480	1,600	4,500
Maximum take-off	2,000	5,000	12,000
Normal fuel	120	400	500
Long range fuel	300	1,000	1,000
Engines	Detroit Diesel or similar, 80 kW	Detroit Diesel or similar, 240 kW + water jet	2 Detroit Diesel or similar, 350 kW + water jet
Fans	2 1.2 m warp drive	2 1.8 m Avia Hamilton V510 Variable pitch and reverse thrust	2 1.8 m Avia Hamilton V510 Variable pitch and reverse thrust
Construction	Carbon fibre, welded aluminium alloy	Welded aluminium alloy	Welded aluminium alloy

Table 2.12 (continued)

Craft type	Sea Wing 02	Sea Wing 05	Sea Wing 12
Take-off speed (knots)	35	40	45
Take-off distance (m)	80–100	100	100
Landing speed (knots)	35	40	45
Landing distance (m)	40–50	50–60	60–70
Operation speed (knots)	40–120	45–160	50–160
Operation altitude (m)	0.3–5.0	0.3–8.0	0.5–12.0
Operating range (n.miles)			
At full payload	630 2 crew + 2 passengers	520 3 crew + 18 passengers	1,800 3 crew + 42 passengers
Long range (crew only)	1,500	1,800	2,600

Radacraft

Rada Corporation of Australia has proposed another design aimed at the Australian tourist industry and perishable goods transport. The craft has a short-span lifting surface with planing outriggers and winglets. The raised tail provides attitude control. Ducted propellers mounted well forward give thrust and also improve lift at low speed by forcing air between wing and ground, see Figs. 2.49 and 2.50 , which show the Radacraft G35 test prototype.

From the figures, it can be seen that it has similarities to the Russian Volga 2. The main particulars of the proposed Radacraft C-850 commercial design are as follows:

Length	10.10 m
Width	8.50 m
Weight	950 kg (empty)
Payload	1,000 kg
Crew	1
Power	2 Rover V8 engines, with 150 hp each
Propulsion	Two-ducted, Multiwing 5Z, six-blade fans
Speed, maximum	130 knots
Cruise	100 knots
Altitude	0.5–1.0 m

Flightship

Flightship bought the technology database, trial craft X-113 (Fig. 1.13) and production prototype FS3-A (Fig. 2.43c) from Rhein Flugseugbau GmbH (RFB) in

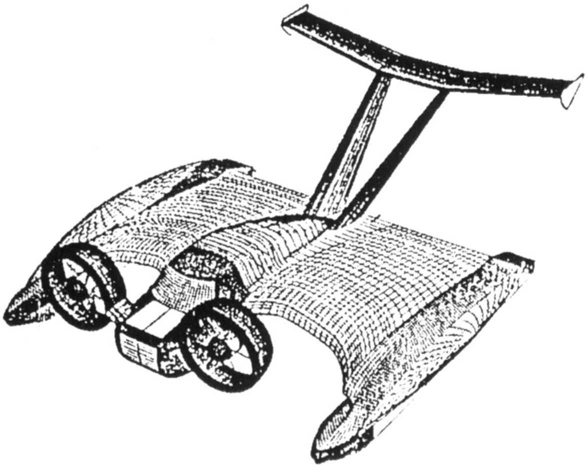


Fig. 2.49 High tail, twin-ducted fan and single hull layout are design features of RADACRAFT WIG

Fig. 2.50 Radacraft G35

1997 at a cost of DM 12 million when its parent company VFW/Fokker went into liquidation.

The original X-113 test craft has been located at Flightship's facility in Cairns, Queensland, and remains in flying condition, though it is not operated. The AF3-A has been developed somewhat and has been used as a flying test bed and pilot trainer while Flightship worked on development of its production designs, the FS8 and FS40.

In 1997, Flightship contracted Fischer Flugmechanik to scale the AF3 design into an eight seater using performance and outfit specifications provided by Flightship. FF completed the design and construction of the prototype FS8 in February 2001. The craft has subsequently completed type certification under the IMO high-speed craft rules by Germanischer Lloyd and Queensland Transport during 70 h of trials.

The FS8 is an all GRP/composite structure following the Lippisch/FF configuration, Fig. 2.51a, b. Power is from a single GM V8 petrol engine mounted behind the passenger cabin at the rear of the fuselage, this drives two 1.7 m open propellers mounted on canted pylons above the rear of the main wing. The high mounted tailplane is supported by twin fins and rudders. The fuselage floats in the water and provides main buoyancy support for the craft. The wing tip side buoys provide for stability while afloat.

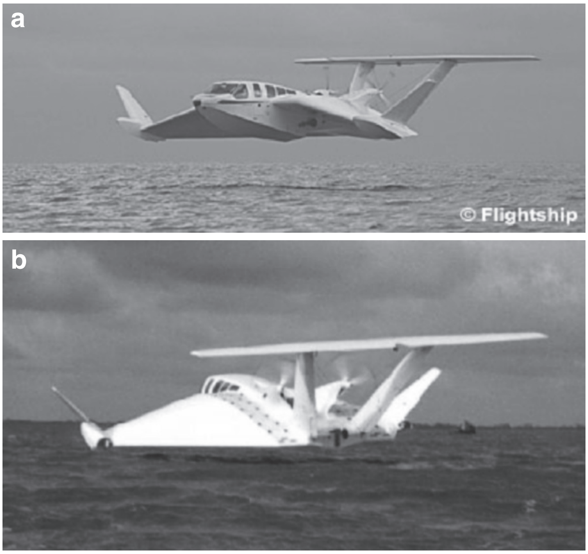


Fig. 2.51 (**a** and **b**) Flightship Dragon Commuter

The Dragon Commuter operates at a flying height up to half the wing span of 15.6 m and so has a considerable operating envelope of up to 2-m seastate for cruising at 158 kph (86 knots). Take-off is possible in up to 0.5 m seas. Lift-off is at 100 kph (55 knots). By selecting large diameter propellers with a low power loading, Flightship has been able to keep noise levels relatively low, at 75 dBA measured at 100 m distance.

The craft has a three-point retractable undercarriage for driving ashore up a ramp, and electric powered water jet propulsors in the side buoys that can propel the craft up to 6 knots. Placed at the wing tips, the water thrusters are clearly useful for harbour manoeuvring.

Flightship craft built in Australia were classified by Lloyds Register. The company developed a scheme for pilot and operating crew training and insisted that clients can only operate with such personnel. This enabled operator insurance and permitting, which otherwise would be difficult since WIG commercial operations are still very new.

The FS40 Dragon Clipper is Flightship's ferry or logistical craft design (Fig. 2.52). It is aimed at 1.2 m seas at take-off and 4 m at cruise speed of 220 kph (120 knots). The design, summarised in Table 2.13 , is configured so that it can take aviation freight containers, passengers, or a mix. Due to the power requirement for this larger craft, two Pratt & Whitney turboprop installations are planned. The larger

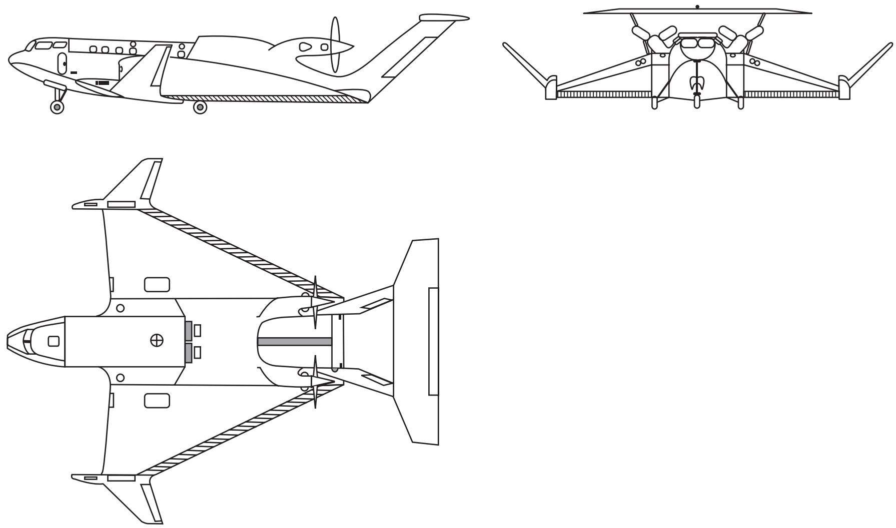


Fig. 2.52 FS-8 Three view

Table 2.13 Leading particulars Flightship Commuter and Clipper

Geometry	FS8 Dragon Commuter	FS40 Dragon Clipper
Length (m)	17.45	30
Wing span (m)	15.6	25
Height (m)	4.1	4.7
Weights		
Empty (kg)	3,740	13,400
Fuel (kg)	180	2,500
Payload (kg)	650	5,000
Maximum take-off weight (kg)	4,750	20,900
Payload fraction	0.137	0.24
Propulsion		
Engine	1 × GM V8	2 × P&W gas turbine
Type	Water-cooled petrol engine	Aviation turboprop motor
Power (kW)	338	1,000 (×2)
(bhp)	450	1,350 (×2)
Propeller	2 off 4 blade 1.7 m variable pitch propellers	2 off 3 blade variable pitch open propellers matched to turbine
Performance		
Take-off speed (kph)	101 at max 0.5 m seas	110
Cruise speed (kph)	158 at max 2.0 m seas	220
Landing speed (kph)	92	Less than 110
Water drives (kph)	11	Tba
Range (km)	550	2,780
Cruise clearance (m)	3	Tba

structural dimensions have meant that Flightship selected aluminium construction for the Clipper rather than GRP

Flightship experienced financial difficulties in 2002/2003 due to the heavy investment programme required for prototype certification prior to sales being possible. The company has since been purchased by entrepreneurs in Singapore with the intent to complete development to commercial viability.

Concluding Observations

We have surveyed the historical development of WIG design up to date in this chapter. The technology has developed a great deal over the last 30 years. At present, the focus is on much smaller craft than Alexeyev and his colleagues designed and operated in the Caspian Sea. Their technical achievement was so enormous that it will be a considerable time before commercial WIG craft of that size and speed are in operation. The outer limits have nevertheless been tested.

Today's challenge lies in developing craft suitable for commercial or logistical service. Work continues in Russia, China, Australia, Singapore, Germany and South Korea to meet this challenge. Differing design concepts have evolved depending on the target cruise speed or craft mission chosen by the particular organisation. A number of common threads are nevertheless evolving:

- Small craft for commuter, ferry and logistics are reaching the marketing stage.
- GRP suits craft for commuter size, while aluminium structure is likely to be more efficient for larger craft.
- Air cushion or lift augmentation is a powerful tool and most helpful in optimising larger/faster craft. It also introduces complexities to control during mode transition.
- Take-off environmental conditions are the most sensitive parameter for a WIG. Improved take-off envelope is therefore a valuable asset to a new design.
- Take-off and landing transition are the most difficult part of WIG design and also their flying technique.
- Different configurations are optimum for recreational and small craft, logistics craft and potential large trans-oceanic craft.

The summary in this chapter has not been exhaustive. There are many individuals and smaller organisations that have designed, built and operated prototypes, with varying amounts of success. Readers will find reference to the "WIG Page" on the Internet web useful for more detailed investigation of different designs.

In the further chapters of this book, we will discuss the theories related to the lifting wing, air cushion and ram lift augmentation, and performance assessment. The aim is to cover the range of parameters such that a designer may work out a design for any of the craft sizes or types mentioned above. The theories and data available are limited in this field, so readers are encouraged to carry out their own research to supplement the material presented here before attempting a build programme!

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