The Main Research Problems Solved in Designing Russian Ekranoplans and which are Necessary to be Solved for Wide Practical Realization of Ekranoplans

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ABSTRACT

The former USSR is among the leading country in the development of ground effect technology. Under the guidance of Rostislav E. Alekseev, a high number of different prototypes and operating crafts were developed and tested.

This experience is presented in this paper that also offers an overview of the main questions to be answered for the wide development of ground effect technology in the future.

ABOUT THE AUTHOR

Deputy Chief Designer of Russian Civilian Ekranoplans Projects, Lenin's prize winner.

Participated to the development of the Russian hydrofoils and ekranoplans such as CM, KM, Orlyonok 2 ...

Author of the following books on hydrofoils and ekranoplans :

– Home Hydrofoils (Sudostroenie Publishers, Leningrad, 1967) in co-authorship with N. A. Zaycev
– Amphistar. The First Civilian Ekranoplan (Sudostroenie Publishers, Saint-Petersburg, 1999) in co-authorship with D. N. Sinitsyn.
– Ekranoplans. Peculiarity of the Theory and Design (Sudostroenie Publishers, Saint-Petersburg, 2000) in co-authorship with D. N. Sinitsyn and others

Also author of a number of the articles of scientific magazines and reports of symposiums proceeding on hydrofoils/ekranoplans (Saint-Petersburg - 1993, Australia - 1996, 1998, Netherlands - 1998 etc.)

THE MAIN PROBLEMS OF AERO-HYDRO-DYNAMICS WHICH WE SOLVED IN DESIGNING EKRANOPLANS

A number of aero-hydro-dynamic problems were solved in creating Russian ekranoplans as principally new kind of high-speed ships. The first task was qualitative/quantitative study of screen effect. This effect was studied in Russia under the guidance of R.E. Alekseev in the late fifties. The researches were carried on the models of the wings and wing systems into the high-speed aero-hydro-tray and with tugging by the high-speed boat. The main qualitative/quantitative results on screen effect were just obtained in these years during developing methods and measurement equipment for studying aero-hydro-dynamics of ekranoplans [1].

I would note follow most important results obtained during that period of the studies :

1. The growth of the wing lift is observed at altitudes (from screen) less than wing chords
2. The screen effect acts most actively at altitudes equal 0.1 - 0.2 wing chord
3. The approximate dependencies of lift factor of lifting wing (with different aspect ratio) from its screen distances were derived from the analysis of the studies implemented to 1960. These relationships became subsequently basis for development of first aero-hydro-dynamic ekranoplan configurations.

But all the same the main problem of the ekranoplan aero-hydro-dynamics which was required to be solved for creating this kind of high-speed vessels was self-stabilization of air wing and wing system in close proximity to a screen. This problem was and is key task for every designer "encroached upon" ekranoplan development. R.E. Alekseev succeeded in getting positive decision of this problems at unprecedentedly earliest possible date and thanks to this fact became the first designer of high-speed shipbuilding in world. In 1974 he developed the first practical prototype of ekranoplan (troop carrying ekranoplan "Orlyonok" for Russian Navy) [1,3]. These achievements were logical results of his preceding design activity.

I remind you about well-known hydrofoils "Raketa", "Volga", "Meteor", "Kometa", "Burevestnik" and others were created for the first time under the guidance of R.E. Alekseev in fifties and sixties of the 20th century [2]. The key problem of its development was self-stabilization of submerged wing and submerged wing system. This problem was solved on the basis of as named "wing shallowly submerged under free water surface" (in world high-speed shipbuilding this effect is known as "Alekseev effect"). The shallowly submerged hydrofoil and the low-flying air wing effect are mirror effects. In the first instance the wing lift is falling at nearing out water surface, in the second - is growing (fig.1).

The great thing is in the both cases there are dependence of changing wing lift from changing its distance to water (screen) surface which makes available decision of movement stability at support surface (screen) problem. We developed the first aero-hydro-dynamic configuration of the ekranoplan under the guidance of R.E. Alekseev in 1960 on the basis of the vessel with shallowly submerged wings. Realization of the first piloted experimental prototype of the ekranoplan CM-1 [1] (fig.2) demonstrated a possibility of solving the problem of movement self-stability within close proximity to a screen.

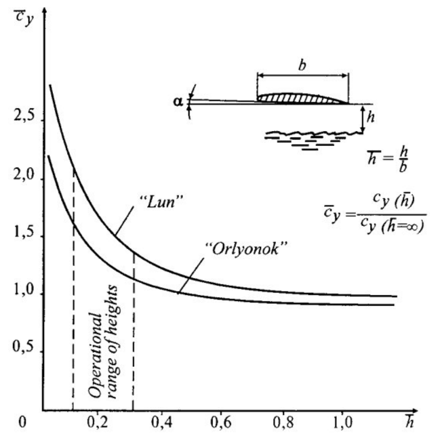

Figure 1 : Typical Lift Coefficient Cy against height

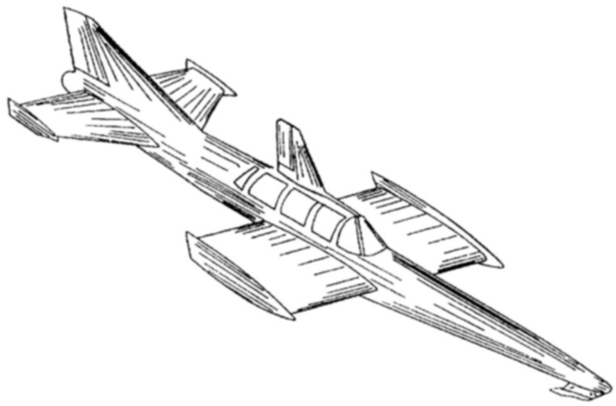

Figure 2 : Self Propelled Model of CM-1 ekranoplan

Nevertheless the test of CM-1 revealed a number of the substantial disadvantages of this configuration (high take-off and landing speed, excessive sensibility of the ekranoplan to roughness of the screen surface and others) which would be problematically eliminated in the first configuration scheme. In 1962 R. E. Alekseev offered one of the most outstanding ideas in the ekranoplan building field without one creating ekranoplan would become insoluble problem. This was the idea of considerable reduction of take-off and landing speeds due to "under wing air-jets" generated by engines. The idea turned out to be extremely efficient, however it was necessary to go over to new type of aero-hydro-dynamic configuration with one lift wing. The horizontal tails afforded the ekranoplan stability as "aircraft configuration". The tails were high lifted for elimination of effecting screen on them. The complex of researches for building a new ekranoplan aero-hydro-dynamic configuration included definitions of a form, aspect ratio and section profile of lifting wing, required power of "under wing air-jets" system and orientation of "under wing air-jets" system with respect to the lifting wing, the geometry of the horizontal tails and its position with respect to the lifting wing. This configuration was developed by R. E. Alekseev in 1962 (fig. 3).

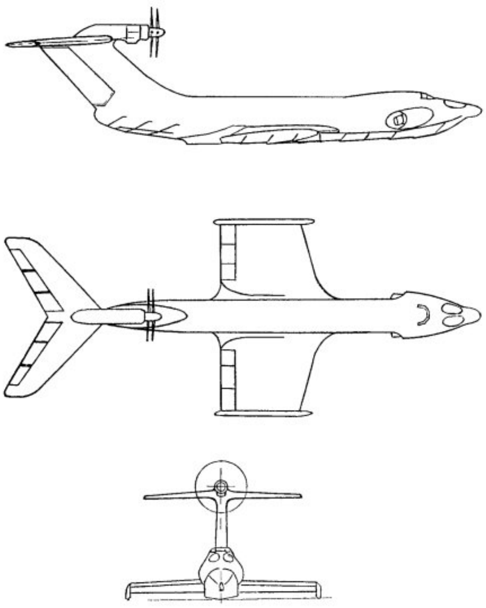

Figure 3 : Scheme of Aircraft Aerohydrodynamic Configuration of Ekranoplan

The basis of this configuration was the lifting wing with one-sided end plates and aspect ratio l = 2. This configuration was intended for solving specific problems of aero-hydro-dynamics and dynamics of ekranoplan motion and therefore had no analogues. Specifically, with using one-sided end plates wing following main problems were solved : decreasing losses and inductive resistance due to the flow of air from the high pressure region on the wing underside to the low pressure region on the wing upside; creating a very efficient dynamic air cushion under the ekranoplan wing and avoiding undesirable "hit" contacts of the wing with a screen during flying. The first time this aero-hydro-dynamic configuration was realized in the experimental prototype of the ekranoplan CM-2 [1]. The results of the tests of CM-2 were in agreement with the design data. In the future this aero-hydro-dynamic configuration became basic one for building Russian the 1st generation ekranoplans : the experimental ekranoplan KM (fig.4) and the first practical ekranoplans for the Russian Navy - troop carrying ekranoplan "Orlyonok" (1979) and attack ekranoplan "Lun" (1987) [3].

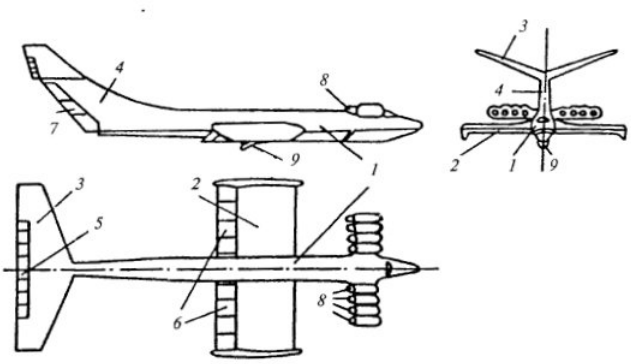

Diagram of aerodynamic configuration of KM

1 — fuselage; *2* — lifting wing; *3* — horizontal tail; *4* — vertical tail; *5* — elevator; *6* — flap; *7* — rudder; *8* — power plant; *9* — hydro-ski device

Figure 4 : Scheme of Aerohydrodynamic Configuration of KM Ekranoplan

This configuration ensured movement stability at speeds in close proximity to the screen up to 500 km/h under no-wind conditions and wave height up to 3.5 m and at weight up to 500 t. The long experience of operation confirmed these features. During 1970's R. E. Alekseev created an aero-hydro-dynamic configuration of the 2nd generation ekranoplan (fig.5). The main problems of creating a new configuration were improving seaworthiness and economic effectiveness.

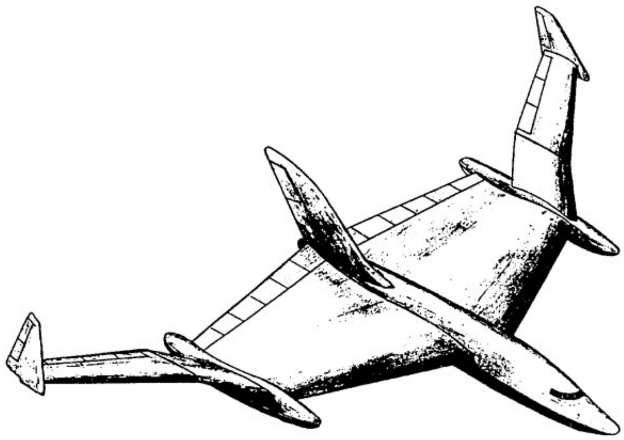

Figure 5 : Scheme of Aerohydrodynamic Configuration of Ekranoplan of 2nd Generation

Unfortunately R. E. Alekseev was unable to complete this work. However the first stage aero-hydro-dynamic configuration of the second generation ekranoplan (fig. 6) was developed under guidance D.N.Sinitsyn on the basis of research experience accumulated in this field.

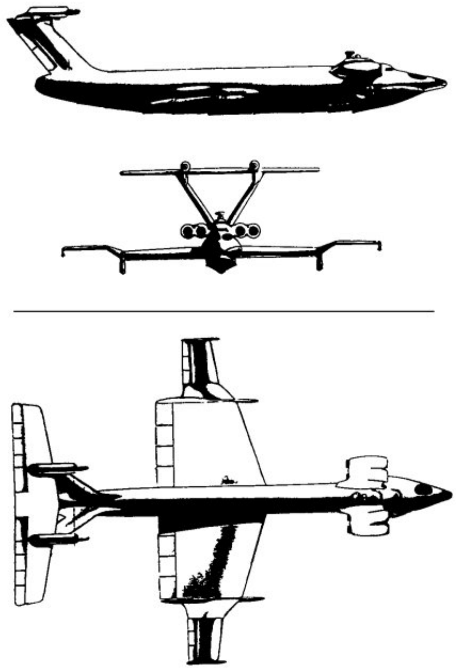

Figure 6 : Scheme of Aerohydrodynamic Configuration of Ekranoplan of the First Stage of the Second Generation

D.N. Sinitsyn proposed a number of passenger and cargo ekranoplans founded upon this configuration. The fundamental element of this configuration was the composite wing with increment of aspect ratio up to $\lambda = 5$. The wing surface area was divided into two functional parts : lifting stabilizing section and lifting section with "under-wing air-jet" maximal efficiency. This configuration provided considerable increase of the ekranoplan aero-dynamic quality and "under-wing air-jet" efficiency (accordingly, increase of ekranoplan flying range and seaworthiness). To decrease the area of the horizontal tail (the area of horizontal tail of the first generation ekranoplans is 50 % of lifting wing plane) S-shaped profile wing was used in the new configuration. It permitted to decrease ekranoplan weight and increase ekranoplan stability and range. Use of flexible pneumocylinders instead of metal hydro-dynamic elements (for cruising and gliding) allowed to substantially decrease the weight and overloading of ekranoplan in take-off-landing modes and to improve ekranoplan's amphibian capabilities. We have found the answer to a number of considered questions that permitted to build the first practical prototypes of ekranoplans and also allows new generation of designers to develop ekranoplans of future.

THE MAIN PROBLEMS ARE REQUIRED TO BE SOLVED DURING CREATING EKRANOPLANS OF THE SECOND GENERATION

The ekranoplans of the first generation, based on so called aircraft aero-hydro-dynamic configuration, were designed in Russia in the early sixties. They were practically realized in military ekranoplans for the Russian Navy : troop carrying ekranoplan "Orlyonok" and attack ekranoplan "Lun". [1,3]. In principal aero-hydro-dynamic configuration we used experience accumulated in the sixties in the field of screen aero-hydro-dynamics and in other spheres of ekranoplan building (hull structures, structures of different ekranoplan's components, power plants, control systems, automatic damping and movement stabilization systems, navigation systems, measurement equipment, etc.), as well as experience derived from testing of the first piloted experimental self-propelled models (including the well-known "KM"), with weight ranging from 3 to 500 tones [1]. This design configuration makes it possible to improve ekranoplan's performance and cost efficiency. The aero-hydro-dynamic quality of the 2nd generation ekranoplan increases, other conditions being equal, from 10-12 up to 25, i.e. twice in comparison with the first generation ekranoplans. Such enhancement of the aero-hydro-dynamic quality is due to increment of aspect ratio of the wing of the 2nd generation ekranoplan configuration up to $\lambda = 5$ and also to considerable decrease of the stabilizing surfaces' area (horizontal and vertical tail). No less important advantage of the 2nd generation ekranoplan is improvement of its seaworthiness by using more efficient "under-wing air-jets" system and flexible ballonets instead of stiff floats. The above-mentioned reasons results in improvement of amphibian capabilities of ekranoplan. The high-speed craft designers' attention is naturally drawn by obvious advantages of the 2nd generation ekranoplans aero-hydro-dynamic configuration under almost all basic characteristics. However, realization of the perspective aero-hydro-dynamic configuration in practice requires some problems to be resolved, otherwise it is unreal to use configuration as it was proposed by R.E. Alekseev.

Movement Stability

Aero-hydro-dynamic configuration of the 2nd generation ekranoplan allows more efficient use energy resources of " under-wing air-jet" engines to enhance "under-wing air-jet" efficiency, i.e. to substantially increase lifting force of the wing per 1 tonne of engine thrust. Realization of this conductive factor for improvement of take-off-landing features, especially seaworthiness, depends on possibility to solve problems of movement stability for these modes. It is known that "air-blow under wing" worsen ekranoplan's features of longitudinal stability. In configuration of the 2nd generation ekranoplan the unfavorable factor (in respect of longitudinal stability) of the maximum reduction of horizontal tail areas is added to that of "under-wing air-jet". Creation and application of automatic damping and movement stabilization system is apparently a solution to the problem of ekranoplan longitudinal stability. But on the way to solving this problem there are some obstacles to be overcome - to create high-precision and safe damping and stabilization systems, which hardly ever get out of order at low screen heights ; to provide a highly efficient longitudinal control under conditions of extremely small horizontal tail area of ekranoplan. In its turn accurate and safe operation of automatic systems depends on precision of instrumentation, that provides data for stabilization and damping systems. Nevertheless, there also remain some problems, being under study - precision of flight altitudes and pitch measurements. In particular, accuracy of pitch measurement in conditions of accelerated (slowed down) ekranoplan movement at take-off (landing) is connected with creation of inertial verticals (gyroscopic, laser...). The solving of stability questions as applied to ekranoplans with a small horizontal tail area during cruising flight relates to the problem of safe operation of automatic damping and stabilization systems because of the same reasons. Movement stability at flying height plays an important role in problem of movement stability. As it is known, an aircraft does not possess such type of stability. Ekranoplan's capability to maintain a defined flying height is conditioned by dependence of aerodynamic and moment characteristics on "screen" clearance. In D.N. Sinitsyn and V.I. Zhukov's papers [2] the analytic expressions for the defined height stability index, so called "binding to the screen", were obtained. This index shows the capability of ekranoplan to keep a certain flight range in proximity to the screen in conditions of given external disturbances or possible material and pilot errors. The question under discussion is normalization of this important ekranoplan's index and definition of the values, which are the most favorable for the passenger exploitation. Subsequently, the construction of different elements of aero-hydro-dynamic configuration and design of automatic stabilization and damping system are supposed to be subordinated to these values.

Economic Effectiveness

The possible maximum coefficient of economic effectiveness Kv (where K - Aerodynamic quality and V - Speed of ekranoplan) can be realized when maximum aerodynamic quality (Kmax) and maximum cruising speed (Vcr) of ekranoplan are achieved. The increment of ekranoplan's speed with constant weight is connected with the opportunity to decrease its lifting force, which can be done in two ways : cruising pitch reduction and wing area diminution. As a rule in cruising flight modes from obtained Kmax the pitch of ekranoplan approximates the minimum magnitude ($\theta = 0 \pm 1°$). Therefore the main reserve of speed increment of ekranoplan is reduction of lifting wing area. However, this reduction has an unfavorable influence on take-off-landing modes of ekranoplan. It results in direct decrease of the wing lifting force (in proportion to the wing area reduction) and indirect one (decrease of the lifting force from "under-wing air-jets"). Ultimately it causes the increment of take-off-landing speed, i.e. deterioration of seaworthiness. In each case a designer decides what to prefer : seaworthiness or economic effectiveness. The universal solution of the problem can be achieved by using on ekranoplans the wing with changeable area, which provides maximum area during take-off-landing modes and minimum one during cruising flight modes. Such constructions are developed and successfully applied for a range of aircrafts (e.g.

"SU"-type airplanes), therefore development and application of these structures for ekranoplans is one of the prospective tasks of enhancement of ekranoplan economic effectiveness.

Seaworthiness

The improvement of seaworthiness of the 2nd generation ekranoplans depends mainly on two factors : more efficient use of "air-blow under wing" in take-off-landing modes and utilization on pneumocylinders as ekranoplan's hydro-dynamic elements. Stability problems, concerning increase of "under wing air-jets" efficiency are mentioned above. The effectiveness of using flexible pneumocylinders instead of metal hydro-dynamic elements, which allow to substantially decrease the weight and overloading of ekranoplan in take-off and landing modes, particularly in wave conditions and to improve ekranoplan's amphibian capabilities is dependent on range of problems - serial production of materials for pneumocylinders, development of their optimal technology, technique of utilization and others. The main opportunities to improve ekranoplans seaworthiness are development and practical realization of different ways of increment of ekranoplan's lifting capabilities in take-off-landing modes (augmentation of wing area, diverse methods of wing mechanization : mechanical and jet flaps, control of boundary layer, etc.) and decrease of take-off-landing speed, and as a result - improvement of seaworthiness.

Power Plant

The principal power plant of ekranoplans performs two main functions - provision of required thrust for different speed of movement and required characteristics of "under-wing air-jets" to obtain efficient take-off-landing capabilities of ekranoplans. In this case power plant must have maximum efficiency in cruising "screen" flight mode. Such requirements for the existing power plants applied in ekranoplan building, shipbuilding and other spheres up to present have not been developed before. Therefore, to provide a perspective aero-hydro-dynamic configuration it is necessary to develop a power plant in accordance with the above-mentioned requirements, considering the necessity of its trouble-free operation near the water surface in conditions of creation of water splash and spray.

Control Systems

Low altitude over surface and short time period available to solve the problems relative to in-flight safety in case of different failures of control systems require some specific operational safety regulations to be complied with. The probability of accidents with an ekranoplan is much less than with an aircraft, since the former has an "airfield" under the wings. Thus, practically always, an ekranoplan is able to make an emergency landing in case of serious failure of control system. However, each landing of an ekranoplan results in considerable loss in economy because the landing is being followed by the take-off, which requires maximum fuel costs under operating conditions of ekranoplan's power plant during the limit thrust modes. From here follow the main regulations for ekranoplan's control systems : maximum operational safety and provision the crew with a precise information about those failures which need an emergency landing. The requirements for automatic control systems of ekranoplans (stabilization and damping systems) also have their specificity, consisting in that these systems are designated not only to provide a steady flight, as for an aircraft, but also (and even to a higher extent) for unsteady take-off and landing modes.

Therefore, for these modes, automatic control systems must have gyro and other verticals, not subject to corresponding accelerations.

Problems of ekranoplan control

Taking into account a specific nature of the flight in a strictly limited screen altitude range, the aerodynamic configuration of ekranoplan is designed in such a way to minimize control actions of the crew during all flying modes. It provides for requirements for making control easier and reduction of risk in case of non-observance of operating limitations and crew's errors. Considering the degree of readiness of these questions at the present time, the aero-hydro-dynamic configuration of ekranoplan of the first stage of the 2nd generation was developed under D.N.Sinitsyn's supervision. A composite wing is a basis of the configuration of the 2nd generation ekranoplans, and it keeps a rather developed horizontal tail, though its area is considerably small as compared with that of the 1st generation ekranoplans. The first passenger ekranoplans are being developed on the basis of this configuration. The first passenger ekranoplan developed by " Technologies and Transport" JSC (T&T) is the five-passenger ekranoplan "Amphistar" provided cruising speed up to 170 km/h and certified by the Russian Maritime Register of Shipping [4] (fig.7).

On the basis of this ekranoplan upgraded serial variant of "Aquaglide" ekranoplan was developed. At the first time "Aquaglide" ekranoplan has been certified by Russian Maritime Register of Shipping in May 2001 and recommended for wide practical usage. (Fig. 8)

Figure 7 : Aquaglide

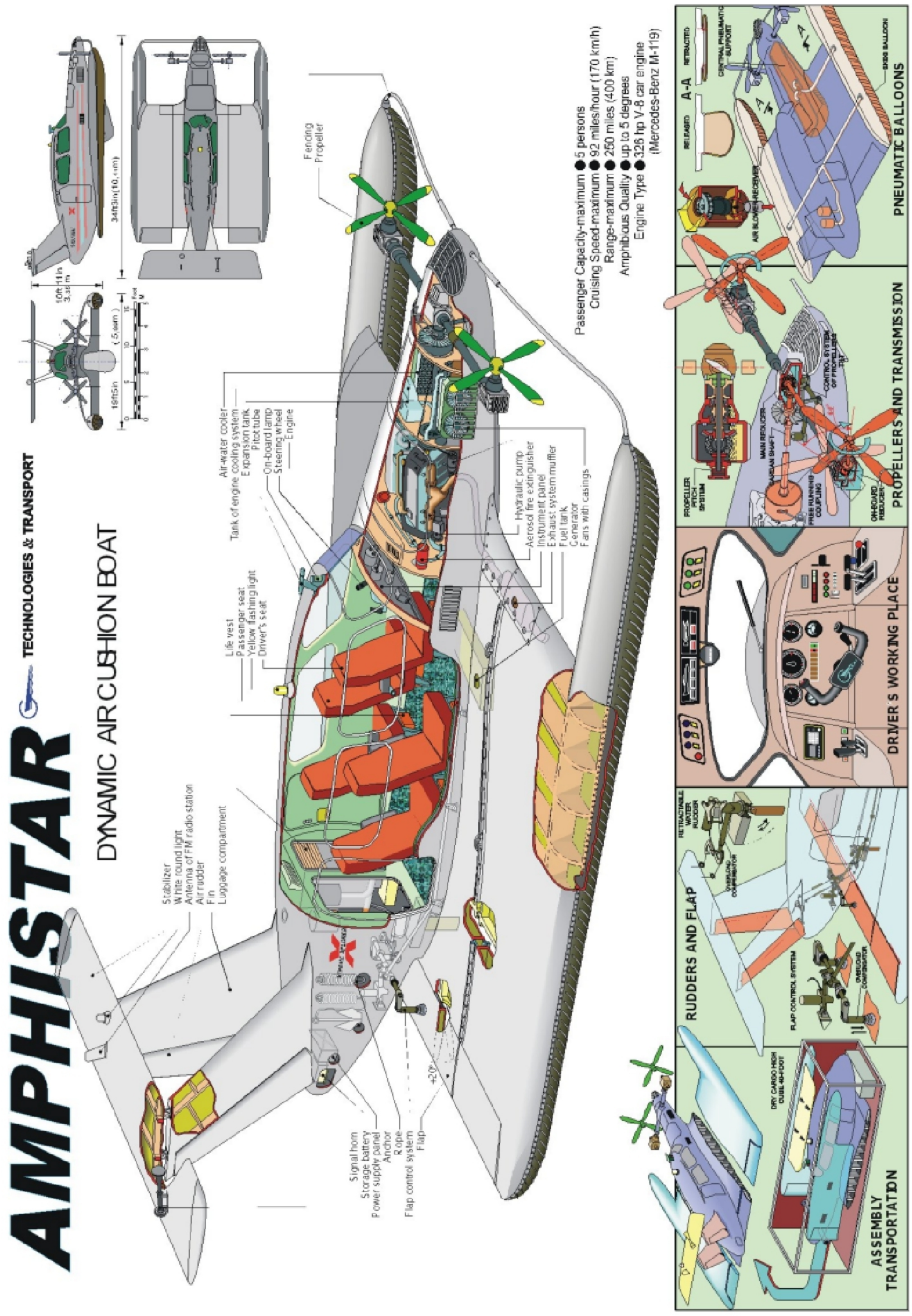

Figure 8 : Aquaglide

Sea-going passenger ekranoplans of the second generation

Project of Ekranoplan	Aerodynamic configuration	Take-off mass(tons)	Overall dimensions $LxBxH$	Wing aspect ratio λ	Type of power plant f-fore a-aft	Maximal thrust P, t, output N, hp	Maximal speed km/h	Seaworthiness
"Amphistar"	Compound wing	2	$11 \times 5.9 \times 3.2$	0.8	Mercedes Benz	N=240	150	0.3
MPE 100	Ditto	100	$41 \times 30 \times 12$	4.5	f : $2 \times D30$ a : $D27$	$Pf = 2 \times 6.8$ $Pa = 14$	380	1.5
MPE 200	Ditto	200	$57 \times 42 \times 15$	4.5	f : $2 \times HK87$ a : $HK15$	$Pf = 2 \times 13.5$ $Pa = 2 \times 15$	410	2
MPE 300	Ditto	330	$68 \times 48 \times 17$	4.5	f : $4 \times HK87$ a : $2 \times HK15$	$Pf = 4 \times 13.5$ $Pa = 2 \times 15$	450	2.2
MPE 400	Ditto	450	$41 \times 30 \times 12$	4.5	f : $6 \times HK87$ a : $2 \times HK15$	$Pf = 6 \times 13.5$ $Pa = 2 \times 15$	500	3

Figure 9 : Aquaglide

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DISCUSSION

Hanno Fischer (HF), Fischer Flugmechaniks

I have two questions. First of all you said that your take off speed with big ekranoplans was about 220 km per hour. I know that with the power augmentation (PAR), you can roughly convert 1 kg of thrust in between 2 and 8 kg of lift. So my question is, according to the fact that you have a very high wing loading, do you use PAR only for take off, or for take off and landing ?

Alexander I. Maskalik (AIM), Alsin - translation Kirill V. Rozhdestvensky

I discussed data related to KM ekranoplan for take off and landing. The wing loading was about 660 kg per m^2. So we produced converting 1 ton of thrust into 9-10 tons of lift for PAR.

HF

Up to 9 tons ?

AIM

Yes. So without air cushion (PAR), the touchdown speed was 220 km per hour which was attained by increased pitch and we used the hydrosky that is very useful to slow down the craft. That was then hydrosky operated with hydraulic systems. We could increase the lift coefficient of about 10% when landing.

HF

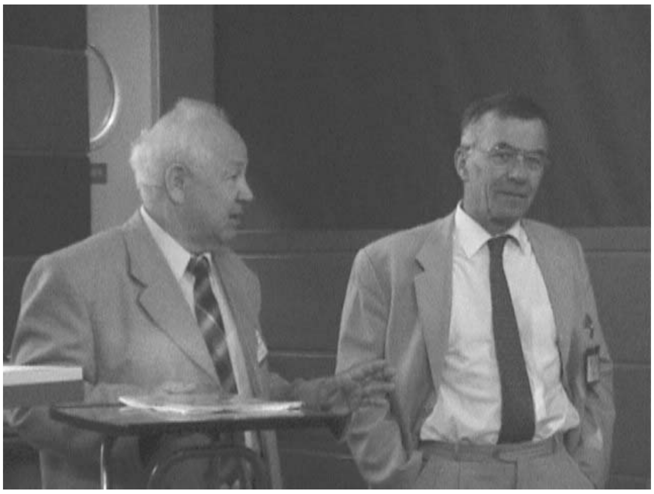
Thank you. But I have difficulties to understand, when you make with 1 kg of thrust 9 kg of lift, and then you lift up at max take off weight at 220 km per hour. How can you reduce your speed without that power augmentation at landing ?

AIM

The PAR is used at landing but as soon as you touch the water. In addition we create the maximum pitch increment. The operations are coordinated between hydraulics and PAR.

Hanno Fischer (HF), Fischer Flugmechaniks

Thank you very much. And the landing speed determinates the maximum loading to design the right structure. So the landing speed is important. My second question then. I could not understand how you go 400 km per hour where you have a very low angle of attack, that means that you'll lose a lot of the advantages of ground effect and a lot of stability. But with such a wing loading of 600 kg per m^2 it is understandable.



Dr Alexander I. Maskalik and Chairman Bernard Masure

AIM

Aerodynamic characteristics at small/zero attack angles ensure perfectly required flight dynamics near a screen.

HF

I estimate that you need 150 kW per ton to overcome the hump drag on take off. Is it a right figure ? The installed power is what determines the economy.

AIM

It is very different from one craft to another. But at take off the ratio of hydrodynamic lift to drag is about 2 or 3. In flight we have this ratio from 12 to 15, so I can not tell you if is correct. But the installed thrust of KM was about 100 tons and 500 tons of weight, so means a ratio is from 1 to 5.

HF

But this is the efficiency of the PAR ?

AIM

When we think about installed thrust, there are 8 PAR engines, so there is only 80 tons for PAR. So it is more efficient than 1 to 5.

Edwin van Opstal (EvO), SE Technology

I have a question about your drawing of the Aquaglide (fig. 8). On the 3 views on the top side, we can see something under the craft. Can you tell us what it is ?

AIM

It is an air cylinder needed for landing.

EvO

But it'll touch the water in cruise ?

AIM

No, it is inflatable.

EvO

So it is only used for landing.

AIM

It is used for landing and manoeuvring situations.

Jean Margail (JM), Airbus

Maybe the last question. You said in your presentation that the Amphistar was a second generation ekranoplan. In which way is it a second generation craft, because you talked about composite wing configurations.

AIM

We have tried to build an ekranoplan of second generation which would have reliable "lashing down" onto a screen. This ekranoplan has an S-shaped lower side airfoil and improved PAR.