Background and prospects for creation of automatically controlled large ekranoplane

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Abstract. The Orlan (Russia) and the Pelican Ultra (USA) ekranoplane projects are analyzed and compared in terms of their design features and applications. Particular attention is paid to the challenges the designers faced while creating ekranoplanes and their control systems. The originality of the tasks that have to be solved by modern and advanced control systems of ekranoplanes, is considered.

Introduction.
Ekranoplanes of various designs and sizes have been the subject of intensive research and development in different countries for several decades, but “ekranoplane industry” is still missing as a sector of transport economics [1-3]. The number of produced small ekranoplanes is measured in tens, though there are only a few large ekranoplanes. The significant advantage of ekranoplanes over aircraft and other vehicles used for typical tasks of transporting cargo and passengers has not been proven yet. However, we can say at last that Russia has got a customer for the development and production of an experimental model of a large ekranoplane. Operational tests of this vehicle in different conditions could allow evaluating its real efficiency.

This is important for making a decision on creating such a heavy multifunctional ekranoplane. At the end of 2018, Deputy Prime Minister Yu. Borisov announced that the experimental ekranoplane Orlan with a take-off weight of 800 tons would be included in the future plan of the development [4-7]. There is neither the aerohydrodynamic scheme nor the concept of building this very expensive vehicle so far. In this regard, any point of view of specialists on these issues requires discussion in order to make the right decision.

It is necessary to take into consideration the Russian experience of creating ekranoplanes Orlyonok and Lun (Alekseev Design Bureau; the damping and stabilization systems for those ekranoplanes were developed in the CSRI Elektropribor) described in publications before 2003, and consider the initial stage of designing the Pelican ULTRA (Ultra Large Transport Aircraft of Boeing Phantom Works). Being aware of the high scientific level and authority of Phantom Works, we will assume that the concept of building the Pelican Ultra was chosen correctly. The project was not implemented. One of the reasons might have been that the project expenses exceeded the customer’s cost limits. Another reason might have been the difficulties associated with integration of the ekranoplane into the existing system of control: neither aviation nor the Navy wanted to take responsibility of the “alien” vehicle, as it was in Russia.

1. Cost estimate.
The cost of manufacturing the prototype Pelican can be estimated using the approximate formula [1,2,15]:

\[ \text{Cost} = \text{Cost of materials} + \text{Labor cost} + \text{Overhead cost} \]
\[ C = K_1 M + K_2 P + K_3 Q, \]

where \( K_1 = 45.8 \) thousand dollars/t, \( K_2 = 1.54 \) thousand dollars/hp and \( K_3 = 25.0 \) thousand dollars, \( M \) is the ekranoplane mass in tons, \( P \) is the total engine thrust in horsepower, \( Q \) is the aerodynamic quality of the ekranoplane in ground effect flight mode. The meaning of this formula consists in a rough extrapolation of the cost of the known built vehicles to obtain the cost of a new more advanced and heavier vehicle. Coefficients \( K_1, K_2 \) and \( K_3 \) are determined based on the experience of the previous projects, so that they make it possible to estimate the cost \( C \) of the heavier ekranoplane Pelican. Substituting the values \( M=2700 \) t, \( P=640 \times 10^3 \) horsepower, \( Q=27 \), the cost of a prototype manufacturing is estimated at $1110M, i.e. 1.110 billion dollars (one billion one hundred and ten million US dollars). This does not include the development cost, which may be 2\( C \).

Probably, after comparing the cost \( C \) with the cost of a B-747 heavy transport aircraft, which was $380M (three hundred and eighty million US dollars), and realizing that they could buy eight B-747 aircraft or ten C-5 Galaxy aircraft (Lockheed Corporation) instead of one heavy ekranoplane, the customers and designers lost interest in the Pelican project.

2. The differences and similarities in the concepts of the Pelican and Orlan.

Pelican [4,5] was designed and intended to quickly transfer military contingents and equipment from the United States to an American military base abroad at any distance. It is cheaper to keep permanent military contingents on the territory of the United States than on foreign bases. The United States has more than 650 such bases, and reducing the staff of each of them to the minimum level for the operation of the base can significantly reduce costs. It is important that most bases have their own runways, suitable for heavy aircraft. Therefore, the Pelican was not designed for landing on water. Like the plane, the Pelican was designed to have only a wheeled landing gear. For the 2700-ton Pelican with 76 wheels, the runway pressure will not be greater than that in the case of a conventional aircraft.

Orlan is a multifunctional vehicle and most of its missions require amphibious capability, in particular, to land on water and take off from water. It was intended for search and rescue operations, transport support for polar settlements, search for spacecraft landing modules, assisting the launch and landing of an aerospace plane, patrolling border areas (especially in the Arctic) with the possibility of emergency landing, firefighting, and rescue of the crew of ships in distress. Therefore, a hydrodynamically perfect hull with water skis, redans, and excessive engine thrust to overcome the “hump” of hydrodynamic resistance is mandatory for the Orlan, but optional for the Pelican.

The Pelican has an original design, since it was for the first time that such a heavy ekranoplane, and the aircraft generally, was supposed to be equipped with a wheeled chassis. The Orlan design is also original, since it is desirable that it can move above water for some distances, “crawl” on a hard surface using a wing blow-up, like the ekranoplane Orlyonok, but not the Lun), and, if possible, have a wheeled chassis for landing on airfields, in particular, for maintenance [6,7], loading ammunition and refueling. However, it is not easy to implement such extensive requirements. They have not been in demand before. Therefore, in the struggle for the financial feasibility of the project, the latter requirement may have to be abandoned.

3. Both vehicles are extremely large.

The design of the Pelican corresponds to the maximum achievable values in terms of size and take-off weight, which is due to the requirement for the maximum load capacity. A heavier version of 4500t was also considered, but finally the developers decided on 2700t [7-8]. The reason is in the available power unit (4 twin engine nacelles with two gas turbine engines each with a capacity of 80 thousand horsepower). More than 8 of these engines did not fit on the front pylon of the Pelican. In addition, the increase in power and mass would require a runway longer than 2400m, which could limit the Pelican’s capabilities.
The Orlan should also be designed to the limit of its capacity and dimensions to ensure seaworthiness up to 7 points, taking into account that it will be equipped with the new PD-35 aircraft engines created by ROSTEC Corporation, which are 3-4 times more powerful than the NK-87 engines installed on the Lun. The Orlan is to be designed to the maximum dimensions, taking into account the capabilities of the hangar necessary for its construction. It is not clear whether the previously used dock of the Volga shipyard, conveniently located on the banks of the Volga River, will fit the size of the Orlan.

**Fig. 1** Ekranoplane (ground-effect vehicle (GEV)) Pelican
4. The airplane scheme.
All of the previously built Russian large ekranoplanes had the aircraft scheme of R.E. Alekseev (1916–1980) with a highly raised tail stabilizer and a rectangular wing of small elongation. Despite its criticism by supporters of the "composite wing" schemes, followers of A. Lippisch (Alexander Lippisch, 1894–1976), the aircraft scheme was successfully implemented in all domestic large ekranoplanes and proved its perfection. The triangular composite wing is used by many companies that are most successful in building small ekranoplanes. A good example is a small ekranoplane AirFish-8 (Fig. 3) developed by WigetWorks [13,14]. However, it would not be wise to ignore the invaluable experience of Alekseev’s Design Bureau when choosing the aerodynamic scheme for the large Orlan. It is highly likely that the Orlan will be built on the basis of the aircraft scheme that has been studied in details.

The experience of the Pelican project can also be used effectively when choosing the concept of the Orlan construction. First of all, the vehicle does not have a raised tail horizontal stabilizer. It is clear that this reduces drag and increases the aerodynamic quality of the ekranoplane, which is good. But how can the well-known problem of ensuring the dynamic stability of the aircraft in the longitudinal plane be solved? The Pelican does not have any additional external structural elements that could ensure the motion stability in the longitudinal plane.
Consequently, correction of the vehicle’s dynamic properties in the unrealized project Pelican was implemented very effectively by means of automatic control. There are no other means to provide the longitudinal stability. Given the current level of development of methods and means of automatic control, it is feasible to make any, even structurally unstable, object of control stable if a fully observable and controlled system is considered, for which it must be equipped with the necessary (large) number of motion parameter sensors and actuators [9-12]. Not only the flight parameters, but also the main disturbances to which the vehicle is subjected, for example, gusts of wind, must be measured practically inertialessly. The local aerodynamics of the vehicle must be accurately represented by the created models, which will make it possible to control and counteract any deviations of the vehicle trajectory in the multidimensional state space of from the desired or even in a certain sense optimal. The problem of fault safety should be completely solved by three- or four-fold structural redundancy. The failure of any element of the control system must be detected, localized and lead to reconfiguration of the control system or at least one of its channels. Further, based on the analysis of the risks of the current situation, a decision is made whether to land immediately or quickly enough. For reasons of absolute flight safety, the ekranoplane must be ready to land or choose the approach direction at any time.

5. Intelligent control system.

For the control system of the Orlan and other Russian ekranoplanes, it is necessary to develop and apply methods of synthesis aimed to fully take into account their features [9-12], to ensure absolutely reliable functioning of the synthesized systems in the entire permissible range of phase coordinate changes, and completely eliminate even a small probability of going beyond such an acceptable range. Ensuring stability should be the main prerogative of the control system. Also, the requirements for the quality of control should also be taken into account, in particular, the speed of performing standard maneuvers and the accuracy of maintaining the required values of flight parameters. Of course, reliable models of all signals and perturbations must be known. The multi-dimensional multiloop control system should be built as an intelligent one, i.e. it should involve all currently known principles of artificial intelligence and perform all control functions better than a human operator (pilot). It is necessary to synthesize and design an automatic system rather than an automated one, completely eliminating any failure in the functioning of the system or the pilot. An intelligent automaton prevents from making unforgivable mistakes. Failures of individual elements of the system, for example, due to electronic warfare, mechanical damage, thunderstorms should lead to reconfiguration of the system owing to its structural redundancy. The modern wide diversity of advanced components for the control system makes it possible to increase their reliability by two orders of magnitude.

An operator in the pilot’s seat can trust the automatic control, formulating general requirements for the flight path. Only exceptional unforeseen circumstances can make the pilot take over flight control, particularly, in emergency landing mode. For the Orlan, such a landing on water or even on ice can be performed with the use of a simplified backup control system.

At the time when Lun was designed, it was impossible to create an intelligent control system because of limitations both in design methods and tools and in the hardware and electronic component base. Now such restrictions have been lifted and the developers of Orlan can implement a modern state-of-the-art system, orienting to 5th-generation aviation and even rapidly developing self-driving cars. This approach to the Pelican design follows from the analysis of the available published data.

Other useful information can be taken from the following quotation: “when flying based on the wing-in-ground (WIG) effect, the Pelican ULTRA would be able to deliver cargo at a range of about 10 thousand miles, but when flying at an altitude of only 6.5 thousand miles” [7, 8]. This means that the aerodynamic quality of the Pelican in the WIG mode, i.e. at an altitude of 6m with a wing chord of 30m (relative altitude 6/30=0.2, which would be difficult to implement for a small ekranoplane), is 10/6.5=1.54 times greater than in the aircraft mode. If we take Q equal to 17 for the airplane mode, then for the WIG mode we have 17×1.54=26.2, which is very good for reducing the cost of
intercontinental transportation. That might have been the goal faced by the Pelican developers with regard to large-scale production. Orlan developers are not so much interested in fuel economy as in expanding tactical capabilities for various tasks, and this does not yet require mass production.

In addition to the new control system, the priorities for the development of new technologies in the Orlan project are the following:

1. Retaining the Lun configuration as a whole, try to improve it locally, using both the old "purges" and performing a large amount of new ones, including virtual (computer) ones.
2. Solve the problem of observability and controllability by improving the types, characteristics, and number of sensors and actuators.
3. Optimize the materials for the body and other elements of the vehicle aimed to reduce their weight owing to composite and other modern materials without changing the aerodynamic configuration.
4. Carry out a special study of the ekranoplane taking off from the waved water surface in order to minimize the required engine thrust.
5. Develop a set of actions aimed at effective use of the ekranoplane in the Arctic.
6. To study the efficiency of using a heavy ekranoplane at launching and landing of an air-space aircraft without a wheeled landing gear by equalizing the speeds, approaching and docking two wing vehicles.

6. Risk factors in the implementation of the Orlan project.

It is clear to everyone that unexpected huge national expenditure to effectively face the pandemic can lead to sequestration of the Federal budget, which adds difficulties to the implementation of the project. It is highly undesirable to reduce the annual funding of the project, extending its duration, but such measures can become unavoidable under force majeure. Complete termination of funding would mean the collapse of the developed concept of the revival of domestic ekranoplane building and the loss of earlier groundwork. It should be noted that the Orlan project has many opponents who struggle for their share of budget funding. Nuclear icebreakers are obviously competitors of ekranoplanes, and after the leader of the 22220 Arctic project was commissioned in October 2020, the Baltic plant will have governmental contracts within these projects for many years to come. A contract has been signed for another 100 million rubles for 2 other vessels of this class. The construction of roads in Yakutia and other regions in the permafrost zone is actively funded. It is clear that administrative and economic structures are not interested in ekranoplanes either; they are focused on buying expensive all-terrain vehicles that can be used in winter conditions and expensive helicopters. In the case of ekranoplanes, flight safety increases by an order of magnitude, and this will reduce the profit of insurance companies.

An objective analysis of the prerequisites for the creation and effective use of large ekranoplanes in these conditions is particularly urgent.

Conclusion.

The differences and similarities in the methods and design criteria of the Russian and American heavy ekranoplanes have been analyzed. The priorities in the development of new technologies for computer-aided design of the heavy experimental ekranoplane Orlan and its information and control integrated system have been formulated. For the first time, an estimate of the aircraft design cost at the initial design stage has been given, based on previous projects of similar vehicles with the known cost. It is shown that the cost of creating a heavy ekranoplane can be an order of magnitude higher than the cost of a heavy transport aircraft with a known aerodynamic scheme (for example, B-747 or C-5 Galaxy).
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