Cost features of designing ekranoplanes and their control systems

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Abstract. The possibility of predicting the cost of construction of a new type of transport vehicle based on analogies with already developed related areas of transport engineering is discussed. Special attention is paid to assessing the complexity of creating ekranoplanes and their control systems. Features of the Arctic application of heavy ekranoplanes are studied in comparison with heavy icebreakers. The originality of tasks that should be carried out by modern and promising control systems is evaluated.

Introduction. Optimization of transport flows is one of the most important problems of modern civilization. It includes not only provision of the most profitable transport routes between two points, construction and repair of the necessary road infrastructure, but also development of new types of vehicles. Amphibious means of transport that can solve the problem of passenger and cargo transportation in the areas with undeveloped transport infrastructure are developing particularly rapidly. Their ability to move quickly over any fairly flat surface makes it very promising to create a number of non-displacement vehicles with different sizes and types, which would allow choosing the most suitable vehicle for each specific transport task, first of all, evaluating the cost indicators of transportation.

The specific cost of transportation should take into account the cost of designing a new vehicle, the cost of its production at a certain batch size, the cost of operation (including fuel consumed) and possible repairs, maintenance, and disposal costs. It is desirable to evaluate all these cost components at the earliest stages of design, which requires the development of appropriate techniques.

Design costs should be limited to a reasonable payback period of about 5-7 years, which makes it necessary to plan in advance the multi-alternative use of the new transport vehicle and not lead to the production of just one copy, as happened in the USSR and later in Russia with the projects of the Buran spacecraft, the A-40 Albatross heavy seaplane, and the heavy aircraft An-225 Mriya. Similar mistakes were made in other countries. For example, the estimate of the Shuttle cost at the early stages of design was significantly underestimated. The real cost (taking into account the expansion of the list of tasks to be carried out) was almost an order of magnitude higher than the estimated one. The project did not pay off economically, although its role in strengthening the authority of the United States as a space country was high. In many cases, cost factors are crucial when forming a transport development strategy, making decisions about the design, construction, and choice of tactics for operating vehicles of any type. Cost planning in the development and implementation of transport projects is a necessary element of developing a sound technical policy in government programs and in business.

The authors have long been engaged in developing methods for designing control systems for such amphibious transport vehicles as airboats, hovercraft and ekranoplanes; in this article we attempt to
offer a simple approximate method for estimating their cost depending on several (in reality, no more than three) main design parameters.

Naturally, research and design work is allocated as a separate item for the cost of transport equipment only in the projects funded by the state. In commercial projects, such investments are covered from the profit, but in any case they affect the price of the vehicle.

1. The Dix-Riddle Method.
The most difficult problem is the cost assessment of the design and equipment of a transport vehicle at the earliest stages of its design. Its approximate solution can be found using the Dix and Riddle formula [1], which drew the authors’ attention in 1994 [2,3]. In this time-tested formula, only three parameters appear: the total mass of the vehicle $M$ in tons, the power available on board $P$ in horsepower, and the serial number of the vehicle under construction $n$. We can write this formula as

$$C_c = K_{inf}(K_1 M + K_2 P n^{-1/3}).$$

Here $K_1$ and $K_2$ are the coefficients known from [1,2], the first of which is measured in thousands of US dollars per ton, and the second, in thousands of US dollars per horsepower. The $K_{inf}$ inflation is the rate coefficient of bringing the cost price to the price level of a particular year. We should take into account the inflation over the years of about 2.5% per year and the corresponding increase in dollar prices. Assuming that by 2020, 15 years have passed since the book was published [2], the corresponding inflation coefficient may be $K_{inf} = 1.025^{15} = 1.44$.

The coefficient $n^{-1/3}$ included in the second term in formula (1) approximately takes into account the factor of serial production, which affects the cost of the vehicle through its serial number $n$, and can become very significant for large values of $n$. Note that the experimentally established law of mass production consists in reducing the cost of a product by a fixed relative value of $\rho$ for each doubling of the series value [4], expressed mathematically as

$$C_{2n}^a = \rho C_n^a,$$

where $C_{2n}^a$ and $C_n^a$ are the average production costs of a single transport vehicle in series of size $n$ and $2n$, respectively. Therefore, $\rho$ is a relative parameter of cost reduction due to the accumulation of production experience. As a rule, $0.75 \leq \rho \leq 0.97$ and the lower limit of the specified interval corresponds to large-scale production (for example, aircraft construction), and the upper limit corresponds to small-scale production. If formula (1) neglects the influence of mass $M$ on the cost of a transport vehicle and controls the average cost in a series of size $n$ for the cost of the $n$-th vehicle, then this formula will actually correspond to the value of $\rho = 2^{-1/3} = 0.80$. This means that the fourth vehicle will cost $80\%$ of the cost of the second, and the eighth $– 80\%$ of the cost of the fourth. Next, we will consider only the case of $n = 1$, i.e. we will estimate the cost of the first experimental sample of a new transport vehicle produced in 2020. If necessary, one can estimate the cost of a series of vehicles or take into account the change in cost over time based on formulas (1) and (2). For the specified special case, from formula (1) we derive

$$C = K_1 M + K_2 P,$$

where $K_1 = 2.1$ thousand dollars / ton, $K_2 = 2.3$ thousand dollars/h.p.

Now we can calculate the estimated cost of specific products using formula (3) and compare it with the currently known cost of these transport vehicles on the dollar market, which will allow us to check the validity of approximate calculations using formula (3). It was made for small ekranoplane Ivolga, for Beriev Be-200, for Beriev A-40 (the production of which will be resumed), for hovercraft Zubr-class, for Antonov An-225 Mriya (the production of which is unlikely to resume, but the values are known), as well as for the Soviet ekranoplanes Orlyonok and Lun, whose cost in the 1970-1980s is difficult to recover, but it is possible to convert the current dollar equivalent according to the formula (3) [16-22]. The results are shown in Table 1.
Naturally, the real values were determined based on publications in the open press about currency contracts concluded or being prepared. The basic design of the transport vehicle was considered without taking into account any special equipment or weapons. For Orlyonok and Lun, the “true” values of the cost were taken as those obtained below by a more accurate estimation method.

Table 1. Estimation of the cost of transport vehicles using the formula (3)

| N  | Vehicles              | M, t | P, h.p. | Q lift-to-drag ratio | C, $thous. market value | C, $thous. estimated cost | Calculation error, % |
|----|-----------------------|------|---------|----------------------|-------------------------|--------------------------|----------------------|
| 1  | Ekranoplane Ivolga    | 5.1  | 860     | 15                   | 1700                    | 1989                     | +17                  |
| 2  | Beriev Be-200         | 43   | 38870   | 15                   | 60000                   | 89500                    | +49.16               |
| 3  | Beriev A-40           | 90   | 111308  | 16                   | 200000                  | 256200                   | +28.1                |
| 4  | Zubr-class LCAC       | 555  | 50000   | 12                   | 80000                   | 116200                   | +45.25               |
| 5  | Antonov An-225 Mriya  | 640  | 111000  | 19                   | 250000                  | 256600                   | +2.64                |
| 6  | A-90 Orlyonok         | 140  | 44300   | 16                   | 76700                   | 102200                   | +33.25               |
| 7  | Lun-class ekranoplane | 380  | 192500  | 17                   | 320000                  | 443500                   | +38.59               |

The last column of Table 1 shows the relative errors in the cost estimation by calculating using formula (3) in comparison with the “true” reliably known values. It can be seen that only three vehicles have an error of less than 10%, but most of the other vehicles have an error of ±20-30%. This forces us to try to improve the accuracy of the estimate. In particular, the role of mass $M$ of the vehicle in the calculations was very insignificant due to the clearly underestimated value of $K_1$. This may be justified for other classes of transport vehicles considered by Dix and Riddle, but for aviation equipment and hovercraft, $K_2$ should be reduced and $K_1$ increased based on the methodology described below.

2. Strengthening the assessment of the cost of a transport vehicle.

Paying due respect to the conscientious work of Dix and Riddle in analyzing the components of the cost of transport vehicles, we will try to improve the accuracy of the estimate by finding more reliable coefficients $K_1$ and $K_2$ by solving a system of equations of the form

$$\begin{align*}
K_1 M_1 + K_2 P_1 &= C_1, \\
K_1 M_2 + K_2 P_2 &= C_2,
\end{align*}$$

where $K_1$ and $K_2$ are the desired unknown values, and all other quantities are known as the features of the transport vehicles. These parameters, which have the first index 1 and the second index 2, are well studied and known. As before, $M$ with the index is the mass of an appropriate vehicle in tons, $P$ with the index – engines thrust of an appropriate vehicle in horsepower. The designation $C$ with the index 1 or 2 is entered – the known cost of the corresponding vehicle in US dollars.

The system of equations (4) can be written in matrix form

$$\begin{pmatrix}
K_1 \\
K_2
\end{pmatrix}
\begin{pmatrix}
M_1 & P_1 \\
M_2 & P_2
\end{pmatrix}
=
\begin{pmatrix}
C_1 \\
C_2
\end{pmatrix}$$

(5)

and its solution is given as

$$\begin{pmatrix}
K_1 \\
K_2
\end{pmatrix}
=
\begin{pmatrix}
M_1 & P_1 \\
M_2 & P_2
\end{pmatrix}^{-1}
\begin{pmatrix}
C_1 \\
C_2
\end{pmatrix}$$

The solution is easily found in general form using Mathcad:
This makes it possible to determine the coefficients $K_1$ and $K_2$ absolutely accurately for the selected base vehicles, and for the other examples of vehicles, presumably more accurately than for Dix–Riddle.

For example, for the ekranoplane Orlyonok and the Be-200 seaplane paired with it, it is easy to use formula (6):

$$
K_1 = \frac{(1700 \times 38870 - 60000 \times 860)}{(43 \times 38870 - 60000 \times 860)} = 89.8 \text{ thousand USD / ton} \quad (7),
$$

$$
K_2 = \frac{(1700 \times 43 - 60000 \times 5.1)}{(5.1 \times 38870 - 43 \times 860)} = 1.44 \text{ thousand dollars/h.p.}
$$

Let us check whether the coefficients (7) allow us to get more reliable estimates of the cost of other transport vehicles using formula (3), taking into account (7). After making calculations, we get the cost for the Zubr-class LCAC $129M, for the seaplane Beriev A-40 $170M, for the aircraft Antonov An-225 Mriya $220M, for the ekranoplane Orlyonok $76.7M, and for the ekranoplane LUN $320M.

Comparing these results with the data in Table 1, we recognize a fairly large spread in cost estimates, which makes us try another option to complicate the estimate.

3. Cost estimation based on three indicators.

Another attempt can be made to improve the accuracy of estimating the cost of a transport vehicle. To do this, in addition to the mass of the vehicle and the engine thrust, we introduce a third important indicator – the transport (aerodynamic) quality $Q$ as the ratio of the weight of the vehicle to the drag force when it moves. The $Q$ value is particularly good at describing the degree of perfection of ekranoplanes and hovercraft. Since the number of parameters to be found is 3, not two, three equations based on the known parameter $M_1, M_2, M_3, P_1, P_2, P_3, Q_1, Q_2, Q_3$ should be written. The corresponding system of three equations in matrix form instead of (5) will be:

$$\begin{bmatrix}
M_1 & P_1 & Q_1 \\
M_2 & P_2 & Q_2 \\
M_3 & P_3 & Q_3
\end{bmatrix}
\begin{bmatrix}
K_1 \\
K_2 \\
K_3
\end{bmatrix}
= 
\begin{bmatrix}
C_1 \\
C_2 \\
C_3
\end{bmatrix}
$$

Its solution in general form gives Mathcad:

$$
\begin{bmatrix}
K_1 \\
K_2 \\
K_3
\end{bmatrix}
= 
\begin{bmatrix}
M_1 & P_1 & Q_1 \\
M_2 & P_2 & Q_2 \\
M_3 & P_3 & Q_3
\end{bmatrix}^{-1}
\begin{bmatrix}
C_1 \\
C_2 \\
C_3
\end{bmatrix}
$$

or

$$
\begin{bmatrix}
K_1 \\
K_2 \\
K_3
\end{bmatrix}
= 
\begin{bmatrix}
\frac{C_1 \cdot Q_1 \cdot P_1 - C_2 \cdot Q_2 \cdot P_2 + C_3 \cdot Q_3 \cdot P_3 + C_1 \cdot Q_2 \cdot P_2 - C_2 \cdot Q_1 \cdot P_1}{Q_1 \cdot M_1 \cdot P_1 - Q_2 \cdot M_2 \cdot P_2 + Q_3 \cdot M_3 \cdot P_3 + Q_2 \cdot M_2 \cdot P_2 - Q_1 \cdot M_1 \cdot P_1 + Q_3 \cdot M_3 \cdot P_3 - Q_2 \cdot M_2 \cdot P_2} \\
\frac{C_1 \cdot Q_1 \cdot M_1 - C_2 \cdot Q_2 \cdot M_2 + C_3 \cdot Q_3 \cdot M_3 + C_1 \cdot Q_2 \cdot M_2 - C_2 \cdot Q_1 \cdot M_1 + Q_1 \cdot M_1 \cdot P_1 - Q_2 \cdot M_2 \cdot P_2}{Q_1 \cdot M_1 \cdot P_1 - Q_2 \cdot M_2 \cdot P_2 + Q_3 \cdot M_3 \cdot P_3 + Q_2 \cdot M_2 \cdot P_2 - Q_1 \cdot M_1 \cdot P_1 + Q_3 \cdot M_3 \cdot P_3 - Q_2 \cdot M_2 \cdot P_2} \\
0
\end{bmatrix}
$$

The initial data for calculations using expression (8) are taken from the technical descriptions of the following well-known transport vehicles.
Source data no. 1:

- Ekranoplane Ivolga: $M_1 = 5.1 \text{ t}, P_1 = 860 \text{ h.p.}, C_1 = $1.7M, $Q_1 = 14$
- Beriev Be-200: $M_2 = 43 \text{ t}, P_2 = 38870 \text{ h.p.}, C_2 = $60M, $Q_2 = 15$
- Zubr-class LCAC: $M_3 = 555 \text{ t}, P_3 = 50,000 \text{ h.p.}, C_3 = $80M, $Q_3 = 12$

As a result of calculations for (8), we get $K_1 = 60.14 \text{ thousand dollars/ton}$, $K_2 = 1.527 \text{ thousand dollars/h.p.}$, and $K_3 = 25.427 \text{ thousand dollars}$.

To test the effectiveness of the proposed method, formula (8) is used to estimate the cost of the ekranoplane A-90 Orlyonok:

- $M_4 = 140 \text{ t}, P_4 = 44300 \text{ h.p.}, Q_4 = 16$

The cost estimation using formula (3): $C = 60.14 \times 140 + 1.527 \times 44300 + 25.427 \times 16 = $76.47M.

The estimate seems to be slightly underestimated.

Source data no. 2:

- Ekranoplane Ivolga: $M_1 = 5.1 \text{ t}, P_1 = 860 \text{ h.p.}, C_1 = $1.7M, $Q_1 = 14$
- Beriev Be-200: $M_2 = 43 \text{ t}, P_2 = 38800 \text{ h.p.}, C_2 = $55M, $Q_2 = 15$
- Zubr-class LCAC: $M_3 = 550 \text{ t}, P_3 = 50000 \text{ h.p.}, C_3 = $80M, $Q_3 = 12$

As a result of calculations for (7), we get $K_1 = 78.53 \text{ thousand dollars/ton}$, $K_2 = 1.22 \text{ thousand dollars/h.p.}$, and $K_3 = 17.16 \text{ thousand dollars}$.

Source data no. 3:

- Ekranoplane Ivolga: $M_1 = 5.1 \text{ t}, P_1 = 860 \text{ h.p.}, C_1 = $1.7M, $Q_1 = 14$
- Beriev Be-200: $M_2 = 43 \text{ t}, P_2 = 38500 \text{ h.p.}, C_2 = $55M, $Q_2 = 15$
- Zubr-class LCAC: $M_3 = 555 \text{ t}, P_3 = 55000 \text{ h.p.}, C_3 = $80M, $Q_3 = 12$

As a result of calculations for (7), we get $K_1 = 45.8 \text{ thousand dollars/ton}$, $K_2 = 1.543 \text{ thousand dollars/h.p.}$, and $K_3 = 24.95 \text{ thousand dollars}$.

To compare the values found by different methods, we will find the average cost calculated by the second method, find the average for all values, and summarize all values and calculation errors in Table 2.

| N | Vehicles          | C, $ thous. market value | C, $ thous. estimated cost 1st method | C, $ thous. estimated cost 2nd method no.1 | C, $ thous. estimated cost 2nd method no.2 | C, $ thous. estimated cost 2nd method no.3 | C, $ thous. average estimated cost 2nd method |
|---|------------------|-------------------------|--------------------------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|---------------------------------------------|
| 1 | Ekranoplane Ivolga| 1700                    | 1989                                 | 1700                                      | 1700                                      | 1700                                      | 1700                                        |
| 2 | Beriev Be-200    | 60000                   | 89500                                | 60000                                     | 60000                                     | 60000                                     | 60000                                       |
| 3 | Beriev A-40      | 200000                  | 256200                               | 175800                                    | 143100                                    | 176300                                    | 165100                                      |
| 4 | Zubr-class hovercraft | 80000                | 116200                               | 80000                                     | 80000                                     | 80000                                     | 80000                                       |
| 5 | Antonov An-225 Mriya | 250000               | 256600                               | 208500                                    | 186000                                    | 201100                                    | 198500                                      |
| 6 | A-90 Orlyonok    | 76700                   | 102200                               | 76470                                     | 65310                                     | 75170                                     | 72300                                       |
| 7 | Lun-class ekranoplane | 320000               | 443500                               | 317200                                    | 264900                                    | 314800                                    | 299000                                      |
4. Estimation of the cost of ekranoplane Orlan.
Let us move on to the solution of the main problem of this article – estimating the cost of building a promising ekranoplane with a take-off mass of 800 tons for the Arctic and other transportation operations. It is important for making a decision about creating such a heavy ekranoplane with a multifunctional use. The total thrust of the engines of such a heavy ekranoplane should be about $250 \times 10^3$h.p. and the aerodynamic quality (L/D ratio) can reach 21. It is assumed that by the promised date of construction of the ekranoplane in 2027, the engines capable of developing this thrust will be created in Russia. When using different values of coefficients $K$ for formula (3), we get an estimate of the cost in three variants. The original formula (3), taking into account (7), gives the cost of Orlyonok at $576.7M. For the values of the two coefficients $K$ corresponding to formula (7), an estimate of $431.8M is obtained. Finally, when evaluating by three coefficients in accordance with (8), we get $407.2M. We can take a certain average value of $470M as a basis for further calculations.

### Table 3. Valuation for the WIG-craft

| N  | Vehicles         | M, t | P, h.p. | Q lift-to-drag ratio | $C$ estimated cost 1 method | $C$ estimated cost 2 method | $C$ estimated cost 3 method | $C_{aver}$, $M  |
|----|------------------|------|---------|----------------------|-----------------------------|-----------------------------|-----------------------------|----------------|
| 1  | Ekranoplane Orlan| 800  | 250000  | 21                   | 431.8                       | 407.2                       | 468.9                       |                |
| 2  | A-90 Orlyonok    | 140  | 44300   | 16                   | 76.4                        | 72.3                        | 83.6                        |                |
| 3  | Lun-class ekranoplane | 380 | 192500  | 17                   | 443.5                       | 311.3                       | 299                         | 351.3          |

So, the problem of a very accurate forecast of the cost of constructing a heavy ekranoplane for Arctic transportation can be considered and solved.

Note that this is almost 2 times cheaper than each of two new nuclear icebreakers Siberia and Ural already ordered at the Baltic plant, the cost of each being 50 billion rubles or $700M [13]. With their commissioning in 2026, the number of Russian nuclear icebreakers will be 5 with a total cost of about $5 billion. With this money, it would be possible to build more than 10 heavy ekranoplanes. Therefore, it is acceptable to spend only 10% of the amount allocated by the state and investors for the transport support of the Arctic on the construction of an experimental ekranoplane with its comprehensive testing in solving many problems and subsequent replication.

The found estimate of the manufacturing cost of one ekranoplane does not include the cost of its design, for finding which it is necessary to take into account the following circumstances.

The declared 800t of the Orlan mass is determined not so much by the amount of cargo traffic in the Arctic or even on intercontinental routes, but by the required seaworthiness of at least 7 points, i.e. the ability to fly using the ground effect, take off and make a safe landing in intense sea waves, i.e. in almost any weather. To lift such a heavy ekranoplane from the water, a corresponding engine thrust is needed. For ekranoplane LUN with a mass of 380t, it was necessary to install 8 maximum powerful engines, for those times NK-87 with a thrust of only 13 thousand h.p. each, which is why this vehicle was jokingly called “engines carrier”. The new ekranoplane requires new engines with a thrust 3-4 times greater than that of the NK-87. Such GE90 engines with 57t thrust at a price of $29M are available on the world market [7], but Russia cannot use them. The program for creating domestic high-thrust engines has been launched, and its cost has recently been set at 180 billion rubles [5], i.e. $2.6 billion.

According to A.Serdyukov, industrial Director of the Rostec Aviation Cluster [5], the company has started developing powerful PD-35 engines necessary for the ekranoplane Orlan, which are needed not only for heavy ekranoplanes, but also for the resurgent production of seaplanes A-40 [6] and many other aviation consumers. The joint company Aviadigatel noted earlier that “on the basis of the PD-35 engine, it is planned to create a family of aircraft engines of various thrust in the future, up to 50
tons of take-off thrust”. The PD-35 prototype should be assembled and tested in 2023 and certified in 2025. But whether Rostec, with the involvement of many of its enterprises, will have time to fully solve all the problems of creating a PD-35 with a thrust of at least 35 tons by 2027 is a risk factor for the Orlan project. Problems with engines should be recognized as the most difficult in the design of heavy ekranoplanes. One of the special tasks is to take measures to prevent an engine accident due to seabirds entering the air intake.

Optimization of the design of the body and other supporting structural elements of the ekranoplane is also a serious design problem. Strength calculations should be combined with Aero-hydro-dynamic calculations. Calculation of the hull non-rigidity characteristics should prevent fluctuations at frequencies of significant wave disturbances, which are dangerous both due to the risk of mechanical damage and due to distortions in the signals of motion parameter sensors. Aerodynamic calculations should provide high (about 25) aerodynamic quality with the active use of modern powerful design automation tools. In particular, the SUAI has a well-developed calculation method based on Comsol Multiphysics [8]. The complexity of the Orlan design makes it relevant; in addition, the place for its construction requires a very large boathouse and specialized equipment. The Volga shipyard, where the Lun was built, may not be suitable for the construction of the Orlan, although the factor of accumulated experience is very important for reducing the cost of the project and ensuring its high quality.

5. The complex of automatic control of ekranoplane Orlan.

Finally, one of the key issues in the design of Orlan is the development of navigation and control systems (i.e. information and control complex) of the ekranoplane. The navigation part can be taken as an aviation unit; there is no essential specifics in it, except for the altitude channel, the measurement error in which should not exceed 10 cm in the altitude range of 0-10m. Options for constructing a channel for measuring flight altitude in relation to the average level of the disturbed sea surface are described in detail in the authors’ publications [2,3,9,11].

However, the control system does not have a close prototype and requires a very large amount of research and special development.

The Smena-3 automatic damping and stabilization system for the ekranoplane Lun was created by the chief designer, Doctor of Technical Sciences V.B. Diomidov, at the Central Research Institute Elektropribor. This analog— in those times—system is described in detail in his book [14], as well as in the book published two years earlier [2], devoted to general issues of flight control near a disturbed surface.

Can an analog system be a good prototype for a modern digital intelligent control system of a very complex original vehicle? In the absence of another prototype, it can, since no other automation systems for large ekranoplanes have been created over the past 30 years. Large ekranoplanes were not constructed, and on small cheap ekranoplanes it was easier to use only manual control. Now the situation has changed dramatically due to the announcement of the Orlan project [12] and repeated accidents of small ekranoplanes due to piloting errors.

The intelligence control system should include the following qualities.

1. Damping of control channels to ensure proper stability of all control channels for a substantially nonlinear vehicle.
2. Warning and blocking erroneous pilot commands from the crew to avoid accidents due to a dangerous set of flight parameter values.
3. Ensuring the fault tolerance for the main elements of the system, especially for motion sensors and actuators, reconfiguring systems when detecting failures of their elements.
4. Optimal balancing of the rudder and flaps deflections to ensure the angle of attack at which the aerodynamic quality of the ekranoplane is maximized.
5. Automation of coordinated turning with a certain roll and increment of flight altitude.
6. Automation of the take-off mode from the waved sea surface, according to the criterion of minimizing the required engine thrust.
7. Optimization of the 3D trajectory of ekranoplane motion with partial tracking of long-period irregularities of the sea surface to minimize the average geometric altitude of the flight over the irregularities and a corresponding increase in aerodynamic quality.

8. Automation of the “hill” maneuver with a change in altitude when flying over a high obstacle.

9. Automatic or semi-automatic execution of a rapid maneuver to prevent collisions with obstacles (especially with high ice hummocks) at a low location of the survey radar.

10. Creation of a modern three-dimensional system for displaying flight navigation information and recommendations to the crew on the choice of a flight path and parameters.

The cost of developing a control system can be estimated based on several approaches, but it is necessary to take into account both the complexity of the work and the capabilities of modern design automation tools.

Let us take into account that about 19 employees of V.B. Diomidov’s laboratory, who worked for about 4 years, directly participated in the creation of the Smena-3 system and, earlier, the simpler Smena-4 system (for the ekranoplane Orlyonok). Consequently, the total amount of money in terms of current salaries was approximately $1 thousand per month for 48 months for 19 employees, i.e. $0.912M. Taking into account the dollar to ruble exchange rate of 0.705 for 1985, this will amount to 643 thousand rubles. This is together with the development cost of 2161 thousand. RUB is less than 1% of the cost of the first finished copy of the ekranoplane Lun, which apparently indicates the initial underestimation of the role of automation by R.E. Alekseev in ensuring reliable safe flight of the ekranoplane. His opinion changed already at the testing stage, which should have been reflected in further work [14]. But this did not happen due to the termination of funding.

According to the data available from the Concern Central Research Institute Elektropribor [15], the true manufacturing cost of the prototype Smena-3 was approximately 660 thousand rubles, and the cost of its development – 2161 thousand rubles. Note that the cost of the serial sample according to this information was declared as 480 thousand rubles, i.e. 73% of the manufacturing cost of the first prototype. From here, one can determine the number of instances of \( n \) from the equation corresponding to formula (2) \( n^{1/3} = 0.73 \), from which \( n = 0.73^3 = 2.57 \).

Since the number of copies cannot be fractional, we assume \( n = 2 \) and conclude that the cost of a serial sample was taken somewhat low in relation to the level recommended by Dix–Riddle, obviously, in the calculation of the really serial production of Smena-3.

Since the cost of developing Smena-3 turned out to be 2161/480=4.5 times more expensive than the cost of a serial sample, this may be a sign of a high complexity of designing a complex system with unique requirements. A similar situation can objectively arise when developing an automatic control system for Orlan.

The cost of developing a control system can be estimated based on several approaches, but it is necessary to take into account both the complexity of the work and the capabilities of modern design automation tools.

Of course, as in any project, force majeure is possible, which can only be objectively overcome with increased funding. It is the control complex that is associated with the greatest number of uncertain factors that create significant design risks. But to create a powerful PD-35 engine, 180 billion rubles have already been allocated [5,6], i.e. 200 times more than the estimate received for the Orlan control system.

**Conclusion.**
A method for predicting the cost of the head copy of a new vehicle with an automatic control system is proposed and tested. On its basis, the projected cost of an ekranoplane was investigated. It was shown that the cost of the lead copy of a heavy ekranoplane with a modern control system for the Arctic will be approximately half the cost of construction of one powerful icebreaker.
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