Analysis of aerodynamic interference of UAV structural elements such as catamaran with partial aerostatic unloading

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Abstract. This article is devoted to aerodynamic studies of one of the promising aerodynamic configurations of unmanned aerial vehicles (hereinafter UAV) of vertical take-off / landing type catamarans with partial aerostatic unloading. The technique of setting up virtual (numerical) experiment is described; the results obtained are analyzed. The authors defined a mutual arrangement of structural elements of the UAV (bearing surface, the cylinder with the carrier gas, propeller), in which they mutually influence (interference) positively on the mode flight (cruise mode) and hovering. An increase in the aerodynamic quality of the apparatus at these modes was confirmed precisely as a result of the positive interference of the structural elements.

1. Introduction
Currently, unmanned aerial vehicles (UAVs) of vertical take-off and landing (VTL), in which the screws in the ring (fans) are used to create thrust and lift, are being actively developed and investigated [1]. One of the most common types of aerodynamic layout of UAV VTL are circuits with several rotors in the ring. The use of several engines allows one to increase the maneuverability of the UAV. There are various combinations of the number of propellers, their position and size. Combinations are possible with the separation of carrier, march and shunting functions of propellers [2]. Also, more and more widespread hybrid UAV schemes with the use of various combinations of elements, traditionally related to different types of aircraft. At the earliest stages of development, one of the requirements is the modularity of the design of the projected device for the subsequent possibility of creating a whole line of devices, taking into account scalability.

An essential feature of the aerodynamics of such UAVs is the need to take into account the interference between individual elements of a dense aerodynamic configuration, and, if possible, to ensure its positive value.

In the laboratory of "Modeling aerodynamics, design and strength of aircrafts" of Irkutsk National Research Technical University (INRTU) within the framework of the grant of the Scientific Council of the IRNITU, a project of a vehicle with partial aerostatic unloading is being developed to monitor emergency situations.

As a result of a priori analysis, the priority scheme of the designed AIRCRAFT is determined. This catamaran is represented by a carrier wing of small elongation, cylinders with a carrier gas, which are developed end washers, and four helical rotary propellers arranged in pairs in front of the bearing surface and behind it symmetrically with respect to the plane of symmetry of the apparatus, as shown
in Fig. 1.

![Figure 1. UAV type catamaran with partial aerostatic unloading. (1 – bearing surface; 2 – cylinders with the bearing gas; 3 – rotary propellers with the screw in a ring)](image)

The subject of the study is the interference of the propeller, balloon and wing.

Scientific hypothesis: for an aircraft constructed in accordance with the catamaran scheme (Figure 1), there is such a mutual arrangement of structural elements at which they realize their positive interference for different flight regimes.

The effect of negative interference between propulsors and a balloon with a carrier gas for an airship of the classical scheme near the screen is described in detail in [3].

Purpose: to ensure the smallest negative and, as far as possible, the greatest positive interference of structural elements in the hovering mode and cruising at a speed of 40 km/h.

2. Setting up a virtual experiment

To conduct virtual aerodynamic research in the software product, "FloEFD" was created as a solid model of the device (Irkutsk national research technical University has educational and commercial licenses of the software product).

The studies were carried out for two flight modes:

- for hover mode
- for steady horizontal flight with a speed of 40 km/h.

Within the framework of this study, a number of limitations were set:

- in the hovering mode, the vector of thrust of the screws is directed vertically upwards;
- in the mode of horizontal flight of the axis of rotation of all screws horizontal, respectively thrust vector directed horizontally. The angle of installation of the bearing surface relative to the longitudinal axes of the cylinders is 2°. Also in the mode of horizontal flight, the pitch angle of the device was assumed to be zero (the longitudinal axis of the cylinders is in the horizontal plane). Thus, according to the plan of the virtual experiment, the horizontal flight is performed at the angle of attack of the bearing surface close to the attack angle, in which Rmax is implemented. The angle of attack of the cylinders at the same time is zero. This is an important condition for ensuring the purity of the experiment, because when this condition is met, an aerodynamic lift force is not created on the cylinders isolated from the wing. Thus, in the case of fixing the lifting force on the cylinders, the nature of its occurrence can be uniquely determined as a result of interaction with other elements of the aircraft structure (hereinafter AIRCRAFT). For the horizontal flight mode, the varied parameters were:
• Dh1 – relative distance from the axis of rotation of the front screw to the longitudinal axis of the cylinder in the vertical plane;
• Dw – relative height of the wing installation (distance between the longitudinal axis of the cylinder and the trailing edge of the wing in the vertical plane, referred to the wing chord);
• Dh2 – the relative distance from the axis of rotation of the rear propeller to the longitudinal axis of the cylinder in the vertical plane.
• The same variable parameters for hover mode are defined as follows:
  • Dh1 – the relative distance from the plane of rotation of the front screw to the longitudinal axis of the balloon;
  • Dw – the relative height of the wing installation (the distance between the longitudinal axis of the balloon and the trailing edge of the wing in the vertical plane, referred to the chord of the wing;
  • Dh2 – the relative distance from the plane of rotation of the rear propeller to the longitudinal axis of the cylinder.

Thus, the multicriteria problem of searching for the maximum positive mutual influence of the elements of a construction is as follows: K=F(Dw, Dh1, Dh2).

Parameter variation ranges are as follows:

• Dh1 = 0; 0,25b; 0,5b;
• Dw = -0,1b; 0; 0,1b;
• Dh2 = -0,5b; -0,25b; 0.

At the stage planning of the experiment, the existing correlation between the parameters was taken into account. For this reason, the factorial experiment for the 3×3×3 plan was not put, and only values of the greatest interest were analyzed in accordance with the a priori representation of the problem.

The system of boundary conditions is defined as follows:

– flight altitude H = 0m;
– the screen is missing;
– for hovering mode, the speed of the screws nhover=6500 min⁻¹;
– for horizontal flight mode, the speed of the screws ncruise=4200 min⁻¹;
– external disturbances (side wind, etc.) are absent.

3. Preparation of the calculation model

For both investigated regimes, an additional boundary condition was the symmetry condition of the model, which made it possible to reduce the number of elements of the mesh by a factor of 2, and, as a consequence, the required computing resources.

The geometric model has undergone a simplification in the part of modeling the nodes of fastening the structural elements (it does not have a significant effect on the parameters under study, but it significantly simplifies the calculation model). The finite-volume mesh of the computational model is executed in automatic mode with a multilevel partitioning taking into account the features of the flow pattern (compaction of the mesh in the zone of increasing the curvature of the model surfaces, etc.). The method for determining the optimal parameters of the computational mesh is described in detail in [4, 5]

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The work was carried out within the framework of the grant of the scientific Council of RINITU "unmanned aerial vehicle with partial aerostatic unloading for monitoring of emergency situations"
The general view of the basic finite-volume mesh is shown in Fig. 2. Local zones are used to define the rotation areas. Each rotating component of the structure is surrounded by an axisymmetric rotation zone, which has its own coordinate system rotating with the selected component (Fig. 3). For the rest of the computational domain, the fluid and gas flow equations were solved in a nonrotating coordinate system. (To obtain an adequate solution, the cylindrical local regions of the computational mesh were also made in the region of the toe of the bearing surface, its trailing edge, etc.) (Fig.4).

To match the solutions obtained in the rotating and non-rotating regions of the computational domain, a special condition is automatically established on the boundaries of the rotating regions. For correct subsequent processing of the calculation results and detection of the interference component in the values of the aerodynamic characteristics, the calculation models of each of the considered structural elements were also prepared separately for the same boundary conditions. It is separately noted that within the framework of the work on the grant of the Scientific Council of the IRNITA, the aerodynamic forces operating on UAVs with specific sizes were determined to fulfill the terms of the technical task of developing ultra-light UAVs. The problem of determining the coefficients of the aerodynamic forces of the structural elements of the apparatus, taking into account their interference, has not been posed and can be considered separately later.

4. Performing calculations
All calculations were performed in static setting (without taking into account the process of entering the mode, as well as transient processes when changing the mode).

The criteria for convergence are determined automatically at the levels recommended by program settings (1% for each criterion). The convergence criteria were: flow rate and pressure.

The degree of initial turbulence of the flow $\varepsilon$ is given at the level $\varepsilon = 0.02$.

Automatic repartition (refinement) of the mesh after each purge in one calculation (Solver Refinement) is disabled.

5. **Processing of numerical simulation results**

As a result of the performed calculations, the distribution patterns of velocity and pressure fields are obtained.

Fig. 5 shows the distribution of pressures on the surface of the wing and the balloon with the carrier gas near the screw rotation zone on the hovering regime. There is a slight decrease in pressure on the surface of the balloon above the plane of rotation of the screw, and a slight increase in pressure below the plane of rotation of the screw. However, below is a much larger zone of more significant pressure reduction, which ultimately determines the negative interaction between the screw and the balloon with the carrier gas.

![Figure 5. An image of pressure distribution on a cylinder surface in the hovering mode](image)

At the same time, a zone of reduced pressure on the upper surface of the wing is detected, which causes a positive interaction of the screw and the wing, which is significantly greater than the negative interaction between the screw and the cylinder. The total interaction of all elements is positive. The resulting pattern occurs only at close relative positions of the elements at distances up to 1D, where D is the diameter of the screw. When the distance of the elements from each other at a distance of 2D interference decreases to negligible values, not allowing them to consider.

In this case, two key points are:

- The plane of rotation of the screw should be at the height of the wing installation:
  
  $\begin{align*}
  D_{h1} &= D_w + bc\cos\alpha_h \\
  D_{h2} &= D_w 
  \end{align*}$

1. The mutuality between the cylinder and the screw is negative, but the presence of a balloon near the screw in the presented layout scheme significantly increases the positive mutual influence between the screw and the wing.
2. The values of the received forces of the apparatus on the hovering regime, as well as for isolated structural elements on the same regime in comparison are presented in Table 1.
Thus, it is possible to obtain a positive interference up to 4% in the hover mode. This confirms the need and importance of research and accounting for the interference of aircraft structural elements, which is also noted in the [6, 7].

![Image of pressure distribution](image)

**Figure 6.** The image of the pressure distribution on the surface in the horizontal flight mode.

Table 1. Interferention in the hovering mode

| Value                        | Parameter               |
|------------------------------|-------------------------|
|                              | P, N   | Ycylinder, N | Ywing, N | ΣY,N |
| as part of the UAV           | 80     | -0.5         | 2.2      | 81.5 |
| individual element           | 78.5   | –             | –        | 78.5 |

An increase in the lifting force of the apparatus is observed up to 3 times in comparison with the sum of the values of the lifting force for individual elements.

To implement the maximum positive interference, the following conditions must be met:

- \( D_{w}\rightarrow -1/2bcos(\alpha_{mp}) \); \( (2) \)
- \( D_{h1}= D_{w}+bcos\alpha_{th} \).

Also, there is a decrease in the aerodynamic resistance of the device compared to the total resistance of individual elements, which occurs not only because of a decrease in inductive resistance, but also, presumably, due to a decrease in the diffusive effect at the junction of the wing and balloon (not specifically analyzed and requires additional studies on larger ones speeds).

The values of the received forces of the apparatus for one of the calculated cases in the mode of horizontal flight, as well as for isolated structural elements on the same regime, are presented in Table 2 in comparison.
**Table 2. Interferetion in the horizontal flight mode**

| Value                        | Parameter          |
|------------------------------|--------------------|
|                              | Ycylinder, N       |
|                              | Xcylinder, N       |
|                              | Ywing, N           |
|                              | Xwing, N           |
|                              | ΣY, N              |
|                              | ΣX, N              |
| as part of the UAV           |                    |
| 27.75                        | 8.94               |
| 43.04                        | 4.96               |
| 70.79                        | 13.9               |
| individual element           |                    |
| -1.34                        | 14                 |
| 17.47                        | 6.6                |
| 16.06                        | 20.6               |

The obtained results reflect the global trend towards the development of non-traditional aircraft schemes with deeply integrated design solutions in terms of providing unique aerodynamic characteristics.

**6. Conclusion**

In the course of work on the grant of the Scientific Council of IRIT, a series of virtual experiments in the software complex FloEFD was performed to analyze the effect of interference of design elements of a UAV-designed catamaran scheme with partial aerostatic unloading. The analysis of the results allows us to speak about the possibility of developing promising UAV non-traditional schemes that provide improved aerodynamic characteristics in different flight modes.

**7. Acknowledgment**

The team of the authors is grateful to Mentor Graphics Development Services Limited, as well as to CAD Flo company for their help in preparation of the calculation model and operational technical support when working with the FloEFD software complex.

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