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Aerodynamic Characteristics and Longitudinal Stability of Tube Launched Tandem-Scheme UAV

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Abstract

Tube launched unmanned aerial vehicles (UAV) are often implemented with aerodynamic scheme with forward and rear wings (so-called tandem-scheme). Specificity of such UAV is that immediately after launch, they have a flight path in which wings are turned from position along the fuselage to flight position in which sweep angles are about zero. UAV aerodynamic characteristics for different wing rotation angles were researched by computational fluid dynamics (CFD) methods (Ansys 16 software). Quantitative results prove that UAV is unstable with wings rotation angles up to 60° because rear wings produce lift ahead of center of gravity. Therefore, low time of wings unfolding is required. For high angles of wings rotation (low sweep angles), UAV model is stable in a wide range of angles of attack. Local aerodynamic defects were found in the area of the rotation units of both wings. Longitudinal vortex along the left side of fuselage was observed, but it does not result in significant roll moment. Further research might include UAV dynamics modelling based on calculated aerodynamics characteristics or flight tests.

Keywords: tandem-scheme UAV, tube launch, aerodynamic performance, flow separation, longitudinal static stability, computational fluid dynamics, Ansys software

1. Introduction

Tube launched unmanned aerial vehicles (UAV) are often implemented with so-called tandem-scheme, i.e., an aerodynamic scheme with forward and rear wings (**Figure 1**). It allows decreasing of the UAV size in folded state inside the tube, e.g., wingspan might be 30–40% <1 for a conventional aerodynamic scheme. So this aerodynamic scheme has become quite widespread in the twenty-first century [1–3].



Figure 1. Tube launched UAVs: “Switchblade,” “Sokol-2,” “Trident” (in folded state).

Specificity of such UAVs is that immediately after launch, they have a flight path in which wings are turned from the position along the fuselage to flight position with sweep angles equal to about zero [4].

The **goal** of this work is the determination of the aerodynamic characteristics of tube launched tandem-scheme UAV after its start, at the time of wings’ unfolding.

2. Object and methods

Analytic methods are not applicable for such tasks because for low-wing rotation angles, there is a high sweep angle and, therefore, a low aspect ratio (**Figure 2**). For such a type of geometry, flat section hypothesis is not correct, and more complicated methods must be used.

In view of the experimental research expensiveness, it is reasonable to determinate aerodynamic characteristics with the help of computational fluid dynamics (CFD) methods. Ansys 16.0 software was used that allows proper determining of pressure distribution throughout

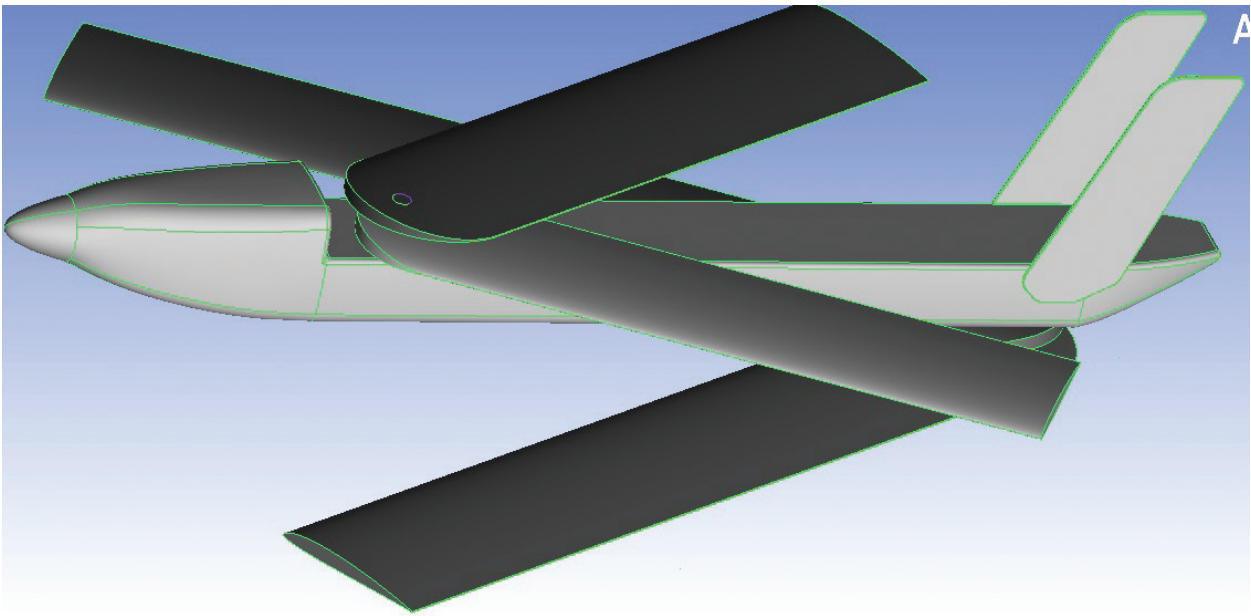


Figure 2. UAV model geometry for wings’ rotation angles equal to 30° (sweep angles equal 60°).

UAV surface and, therefore, appropriate lift and moment coefficients (**Figure 3**). Unstructured meshes were built, and the results independence of cells number was proved for every case. One wing chord equals 110 mm and maximal size of mesh elements are following;

- inlet and far-field—500 mm;
- pressure-outlet—400 mm;
- wing, fuselage—10 mm;
- fins—5 mm;
- fuselage nose and wingtips—2 mm;
- leading edges curves of wings and fins—0.5 mm; and
- trailing edges curves of wings and fins—1 mm.

Total height of prism layer is 2 mm which approximately corresponds to maximal boundary layer thickness at wings' trailing edges. There was only one layer of prismatic elements, i.e., mesh was not sufficient to present shear stress and friction drag values in the boundary layer, but as lift and moment coefficients were the priority of this research, this approach that saves a great amount of time is appropriate.

Domain size equals to about 18 spans of rear wing as a larger model dimension. Mesh created in ICEM CFD software was converted to a polyhedral type that decreases calculation time greatly. Final mesh consists of 1.0–1.5 millions of polyhedral cells depending on the wings' rotation angles value.

Use of Menter's turbulence model ($k-\omega$ SST) is recommended for aerodynamic characteristics' determination at low and high angles of attack when separation occurs [5, 6]. Only a steady case was considered. A pressure-based solver was used with a coupled scheme and a second-order upwind for all available parameters. Computation model includes

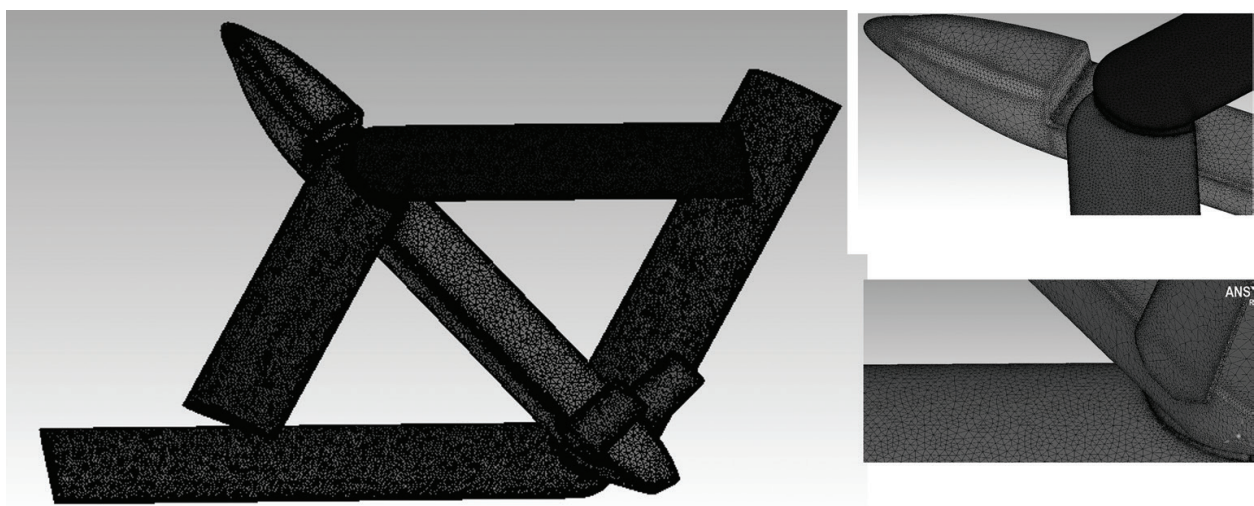


Figure 3. UAV surface mesh with wings' rotation angles equal to 60°.

energy equations as well. Air density was defined as ideal gas, and viscosity was set according to the Sutherland model. Pseudo-transient factors and all unmentioned parameters were set on default. All UAV surfaces had roughness equal to 0.05 mm according to wind tunnel model demands. Gauge pressure of 101,325 Pa, velocity of 25 m/s, and temperature of 288 K were set. Calculation process was finished after all residuals had reached 10^{-4} . For high angles of attack, this threshold was not always achievable, so iteration process was stopped after residuals had become minimal and force coefficients had become about constant.

The object has typical geometric parameters of tube launched UAV with equal chords of all wings and the rear wing span slightly bigger than the forward wing span. In the unfolded state, distance between leading edges of forward and rear wings (stagger) was equal to about 4 chords of one wing. Vertical gap between forward and rear wings from one side is about 70% of wing chord. Gap between left and right wings equals 10% of wing chord, i.e., slightly bigger than airfoil thickness. Wings' rotation angles of 15, 30, 45, 60, 75, and 90° were considered (equal for forward and rear wings). So wings' rotation angle of 15° means forward wing swept angle of 75° and rear wing swept angle of -75°. Reynolds number corresponded to one wing chord and is 110,000. Forces and longitudinal moment coefficients are calculated relatively to the total area of all wings, and moment coefficient is calculated relatively to sum of forward wing and rear wing chords. Moment characteristics were defined for conditional center of gravity (CG) that is placed between axes of wings rotation at the distance of 40% from forward wing axis.

3. Results and discussion

Modelling with the help of CFD methods allows getting forces and moments' coefficients, pressure distribution, and pathlines over UAV model for different wings' rotation angles and angles of attack.

Qualitatively, lift coefficient dependences on the angle of attack are analytically predictable as for higher swept angles (lower rotation angles) lift slope is lower, maximal lift coefficient is lower, and critical angle of attack is higher (**Figure 4**).

Calculated UAV polars for different wing rotation angles can be used for relative comparison only (**Figure 5**), as the mesh in boundary layer does not have appropriate density (number of layers and first layer height) to compute drag coefficient properly. So absolute values of drag calculated are not reliable.

Quantitative results prove that UAV is unstable with wings' rotation angles up to 60° (**Figure 6**). Pressure distribution visualization demonstrates that under-pressure zones at upper surfaces of wings are situated ahead of center of gravity (**Figure 7**). So forward and especially rear wings produce lift ahead of center of gravity that results in negative moment and longitudinal static instability. Of course, center of gravity cannot be moved forward because it would be situated ahead of extreme forward CG limit in unfolded position (zero swept).

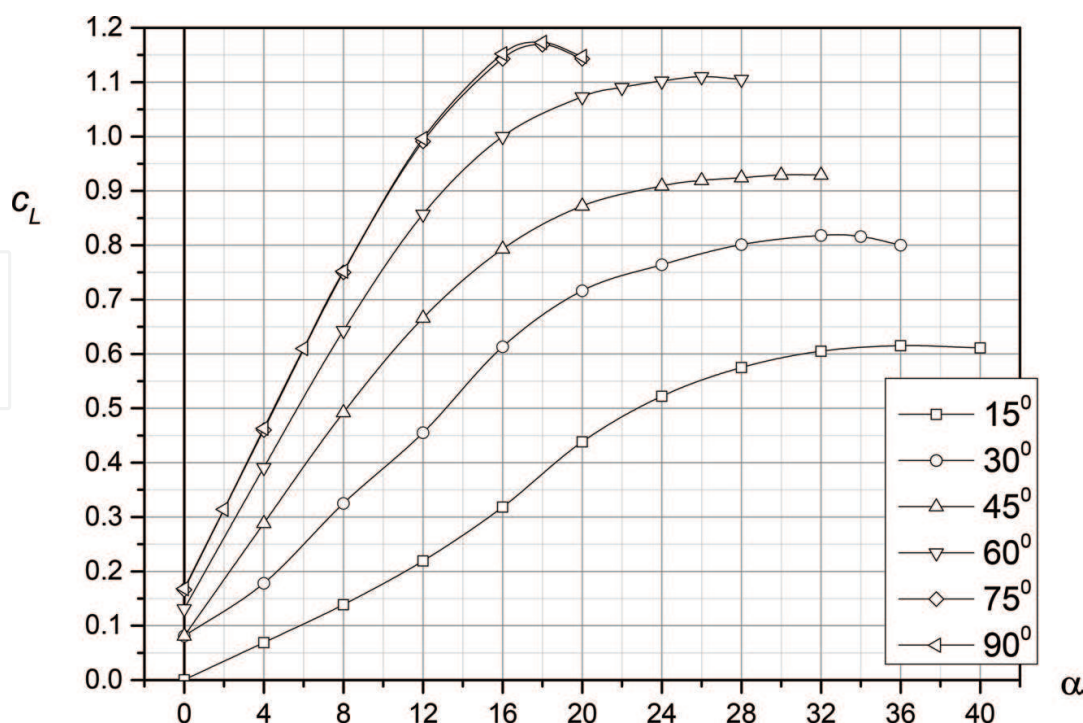


Figure 4. Lift coefficient dependences on angle of attack for different wings' rotation angles.

Obviously, longitudinal instability in wings' rotation angles up to 60° happens not for the given geometry only, but for the different folded tandem-scheme parameters (wingspans ratio, stagger, and height). From the construction point of view, it is rational to fold rear wing ahead and forward wing aft; it is complicated to change design of tube-launches UAV greatly. Telescopic wings may be the solution, but they are associated with design complexity, lower reliability, and airfoil thickness increasing (though bigger profile drag is compensated with high wing aspect ratio and significant induced drag reduction). It is also interesting to rotate forward wings and rear wings differentially (e.g., when forward wings have swept angles of 45° , rear wings have rotation angle of 15°), but obviously rear wing negative pitch moment at rotation angles of $15\text{--}30^\circ$ is higher than positive pitch moment of forward wing (that is also maximal at rotational angles of $15\text{--}30^\circ$). It may be considered in future research, though the maximal effect of differential wing rotation is the decreasing of instability rotation angles range.

So the most simple practical way is to unfold wings very fast, so the pitch moment does not change the angles of attack significantly.

For high angles of wings' rotation (low sweep angles), UAV model is stable in a wide range of angles of attack because separation occurs mainly from forward wing and from root sections, so the model has no tendencies to roll or to spin. Protection from spin is the advantage of tandem-scheme compared with traditional aircraft, for which separation beginning on root sections does not guarantee spin security. Indeed, if at high angles of attack, pilot or UAV operator deflects the rudder, then sideslip occurs, separation may be eliminated on one wing (e.g., left) and enlarge on the other (right wing), so the aircraft may get into a spin. Nevertheless, for tandem-scheme separation, zone on forward wings would be still much bigger than on rear wings, so the aircraft's nose goes down and away from the dangerous regime.

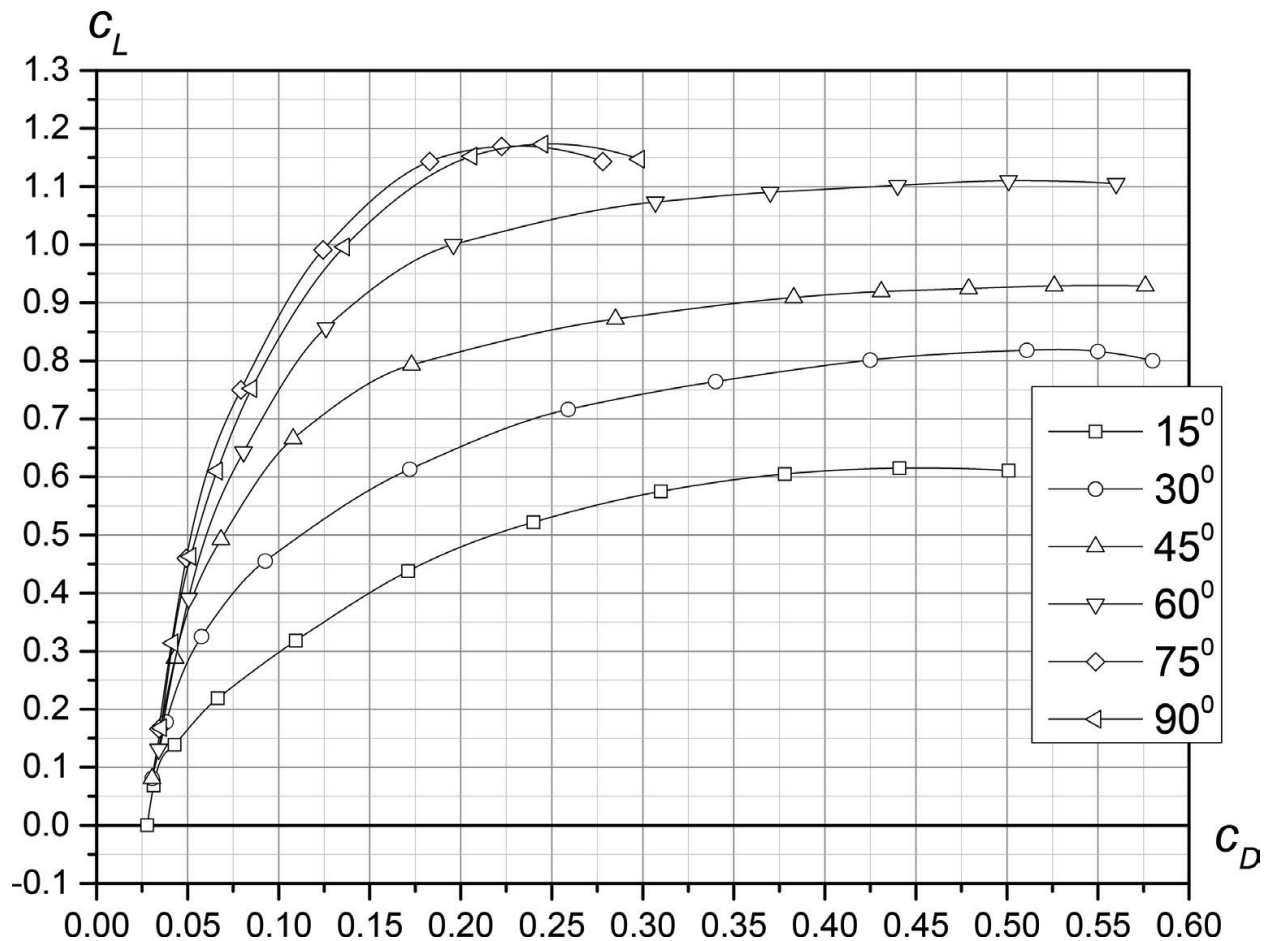


Figure 5. Polars for different wings' rotation angles.

At very high angles of attack, UAV stability is close to neutral (separation occurs on both forward and both rear wings), but the effectiveness of the rear wing ailerons might be reduced due to forward wing tip vortex that increases the angle of attack at tip sections of rear wing that results in small separation areas (**Figure 8**). It does not result in controllability loss, and ailerons on the rear wings are more effective than on forward wings due to larger arm of force. To prevent aileron efficiency, reducing dihedral angles of both wings might be used that decrease negative aerodynamic interference and forward wing tip vortex effect on flow over rear wing (it also can improve lift-drag ratio). The other way is a negative twist of rear wing to decrease local angles of attack for aileron sections.

Local aerodynamic defects were found in the area of the rotation units of both wings (**Figure 9**). Such defects are inherent to folded UAV and may be eliminated with help of flexible fairings that are pressed to the fuselage and wings and slide on their surfaces. However, such installations worsen UAV exploitability because of its permanent deformation and scratches on surfaces and lift-drag ratio remains lower than for UAV without rotation units. It is natural that such fairings were not found on any analogue.

As the folded left and right wings have common axis, and the right wing is situated higher than the left one, there is asymmetry in flow over wings, and a vortex along fuselage's left side is

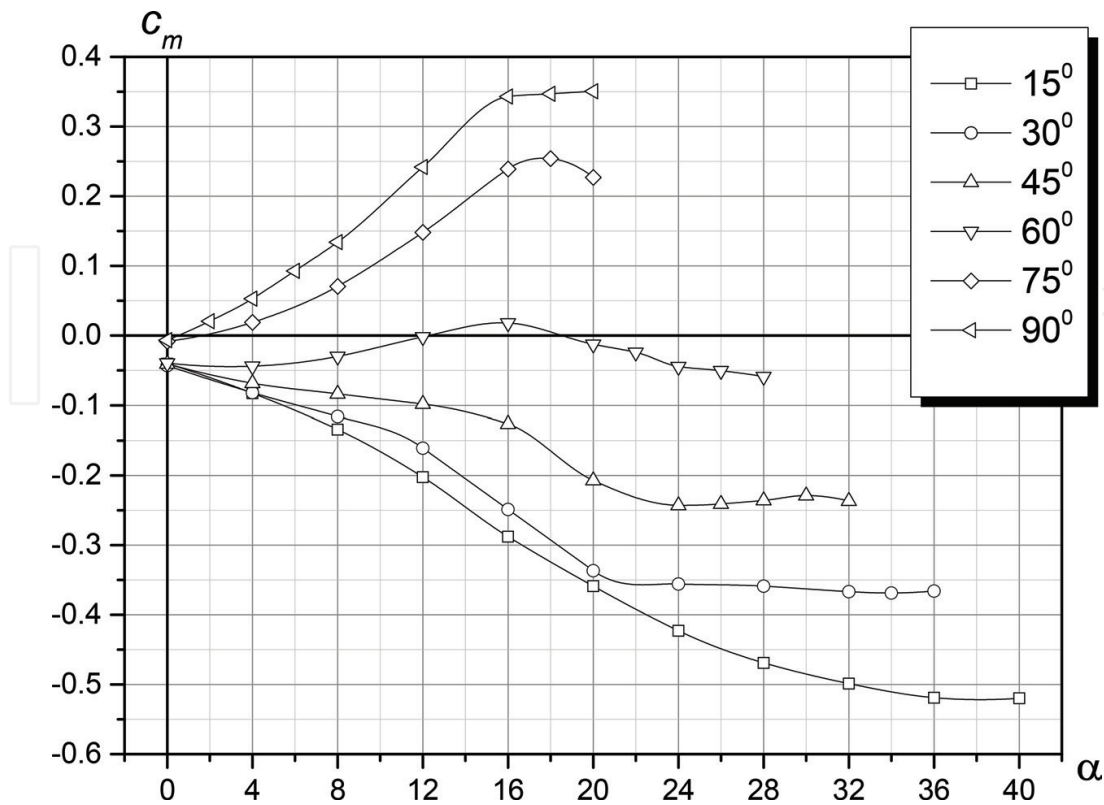


Figure 6. Longitudinal moment coefficient dependences on angle of attack for different wings' rotation angles.

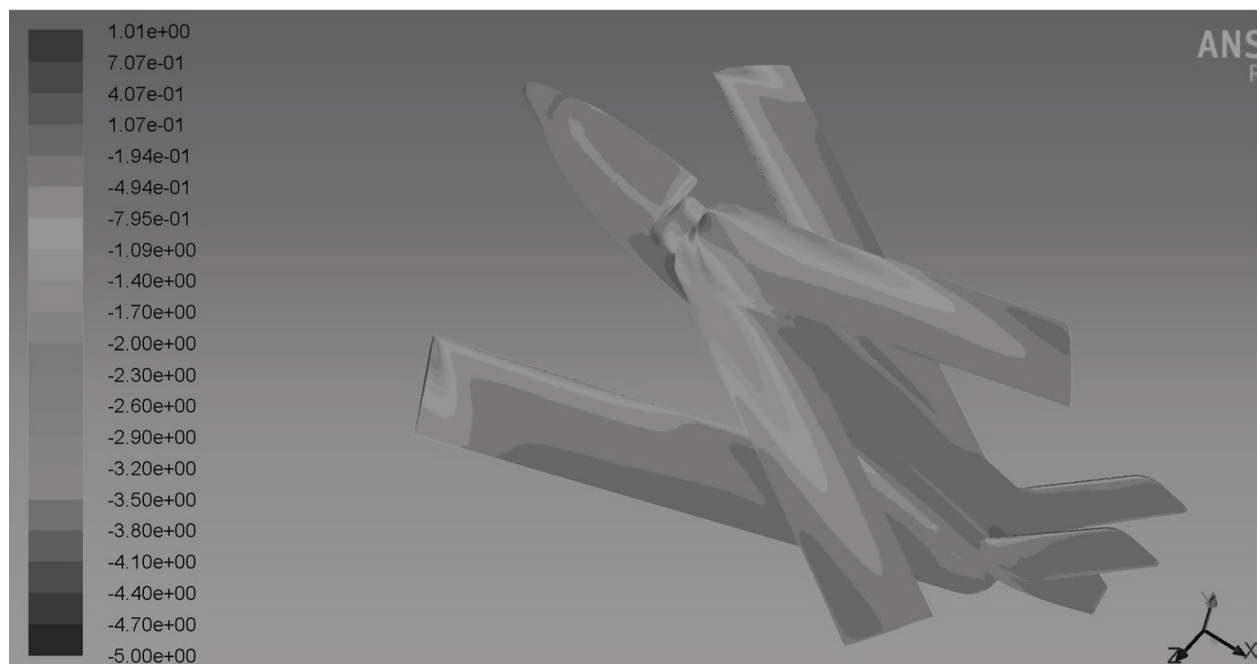


Figure 7. Pressure coefficient distribution (rotation angles 30° , angle of attack 16°).

generated (Figure 10). As this vortex is close to symmetry plane, it does not result in a significant roll moment in a wide range of angles of attack (Figure 11), and there is no preconditions for UAV spin. The only drawback of this vortex is aerodynamic drag increasing due to flow energy loss.

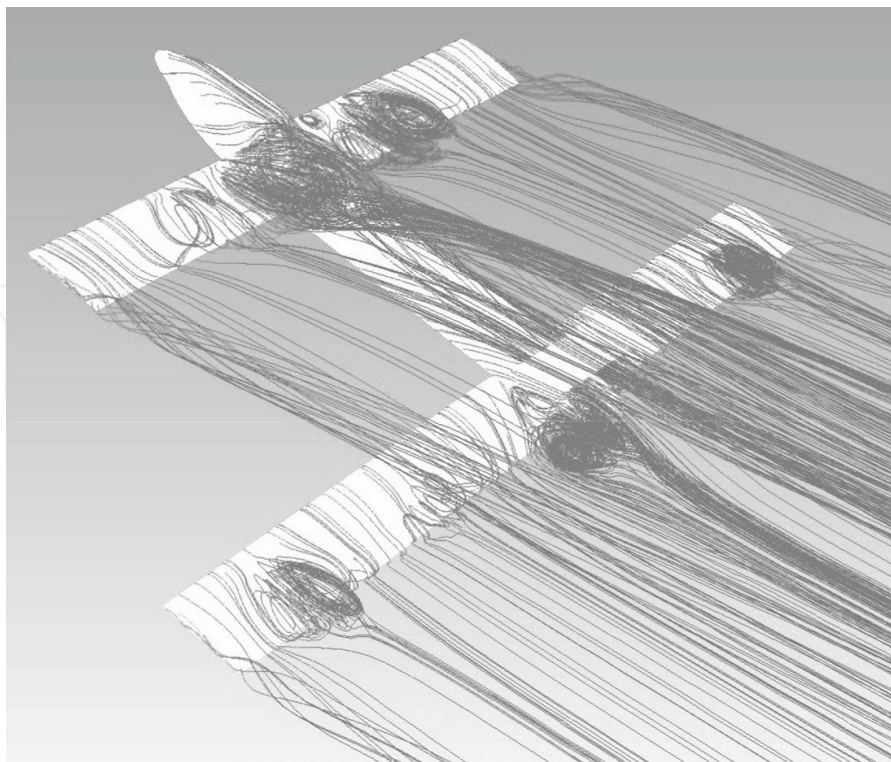


Figure 8. Flow separation from both wings including rear wing aileron sections at high angles of attack.

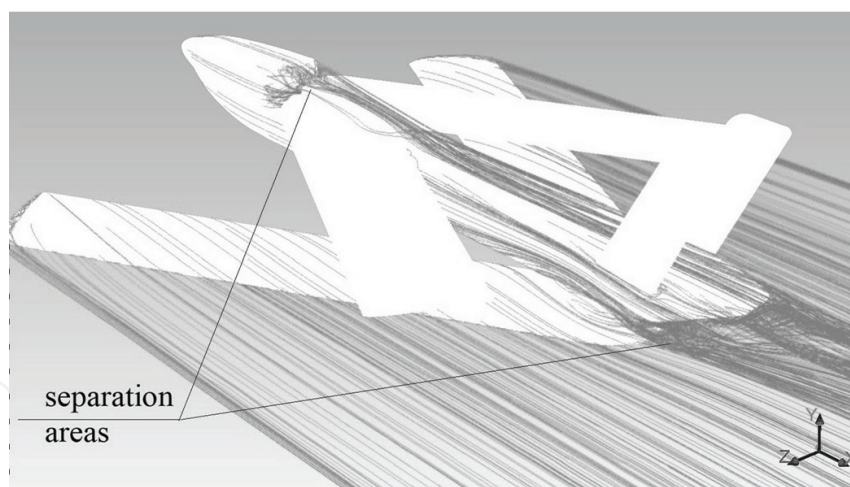


Figure 9. Flow separation after rotation units at low angles of attack.

Also for low wing rotation angles at middle angle of attack, the flow over rear wings is symmetrical, but the flow differs significantly over forward left and right wings (**Figure 12**). Vortex from wings' rotation unit is located over right wing.

It might be interesting that for low rotation angle wings, the pair of vortices is generated: first one is along leading edge and second one is along trailing edge (**Figure 13**). Rear wings vortices go on forward wings, so one complex vortex system is generated by the whole model.

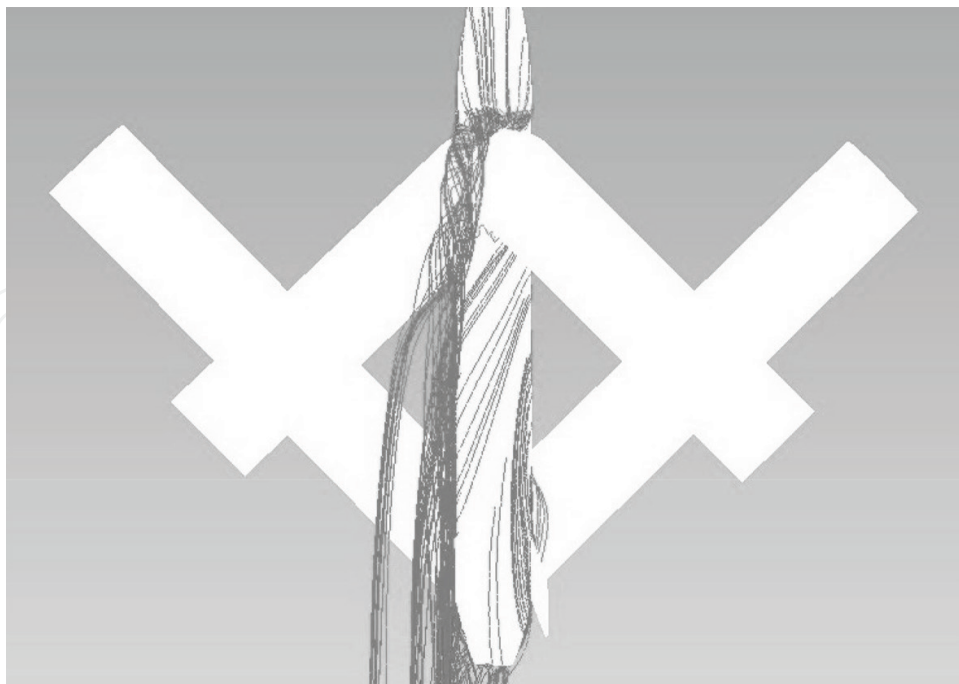


Figure 10. Vortex along fuselage's left side.

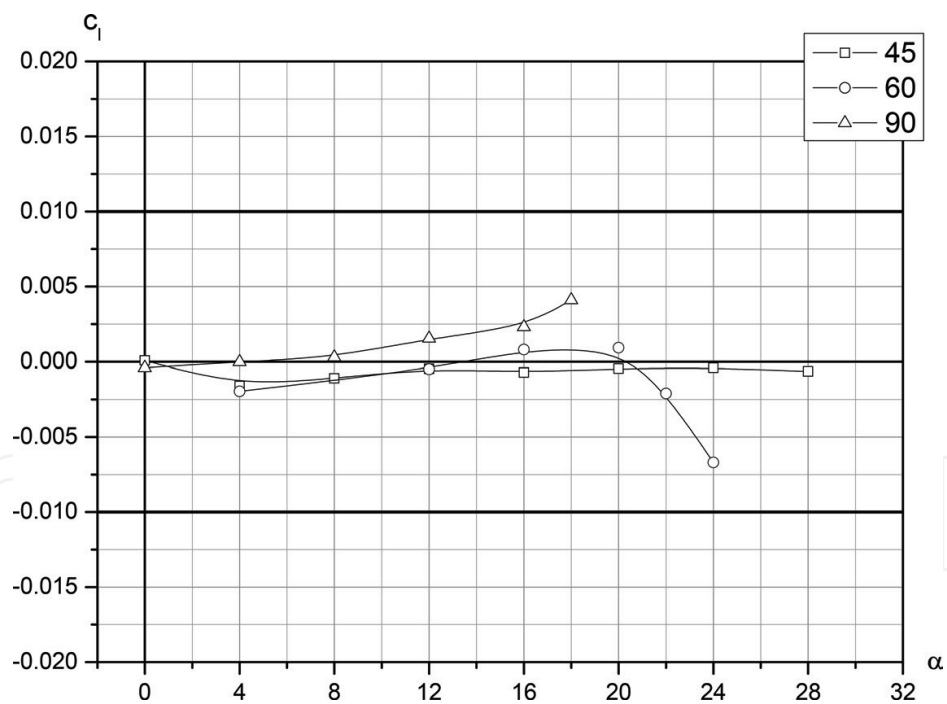


Figure 11. Roll moment coefficient dependences on the angle of attack.

For high angles of attack, separation on rear wings begins at right side because of negative wing-fuselage aerodynamic interference (**Figure 14**). Due to the fact that rear left wing is located lower than the right one, its interference with fuselage is weaker, and there is no



Figure 12. Vortex over forward left wing (rotation angle 15° , angle of attack 24°).

such separation zone. Forward wings are high-wings, so there is no negative interference with the fuselage.

As for tandem-scheme, distance between center of mass and vertical tail is relatively lower than for traditional aerodynamic scheme, so two fins are often necessary to provide yaw stability. As fins also rotate after launch, there are small separation areas after them (**Figure 15**). These aerodynamic defects also may be healed with some flexible fairings as for wing rotation units.



Figure 13. Vortices from rear wings go on forward wings (rotation angle 15° , angle of attack 24°).

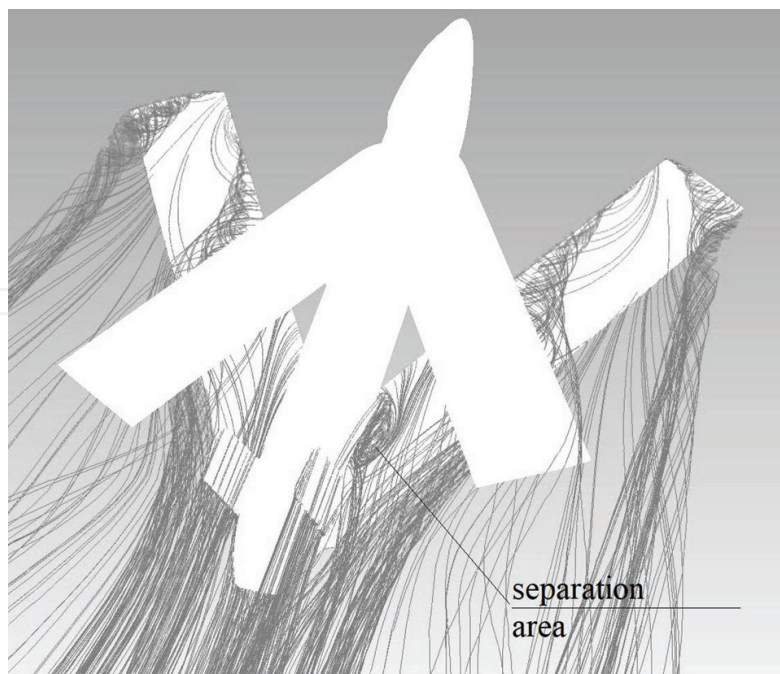


Figure 14. Flow separation on root sections of rear right wing (rotation angle 30° , angle of attack 20°).



Figure 15. Flow separation after fin (rotation angle 30° , angle of attack 0°).

4. Conclusion

Quantitative results prove that UAV is unstable with wings' rotation angles up to 60° because rear wings produce lift ahead of center of gravity.

For high angles of wings, rotation (low sweep angles) UAV model is stable in a wide range of angles of attack because separation occurs mainly from forward wing and from root sections, so despite UAV asymmetry, it does not have tendencies to roll or spin.

Local aerodynamic defects were found in the area of the rotation units of both wings. A longitudinal vortex along the left side of fuselage was observed. It is generated due to model asymmetry so that the right wings are higher than the left ones. It was shown that this vortex does not result in significant roll moment.

Due to UAV longitudinal instability for small wings rotation angles, low time of wings unfolding is required.

Further research might include UAV dynamics modelling based on calculated aerodynamics characteristics or flight tests.

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