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DYNAMICS OF A VORTEX RING AROUND A MAIN ROTOR HELICOPTER

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Abstract

The main goal of the work was an analysis of the dynamics of vortex ring formation process and determinants of the occurrence of vortex rings state (VRS) in a main rotor of a helicopter. VRS occurs in the vertical decent of a helicopter (or close to this maneuver). The paper presents a results obtained by CFD analysis and from the wind tunnel test investigation. The visualization of a flow field provided information on the changing nature of the flow in the course of the movement of helicopter.

Nomenclature

v	forward speed
w	descent velocity
v_{io}	induced velocity
D	rotor diameter
C_D	drag coefficient
C_L	lift coefficient
α	angle of attack
φ	pitch of angle

1. Introduction

In recent years, the use of helicopters increased. Their advantage is the ability to perform flights in each direction at low altitude and low speed and the ability for hover performance. Helicopters are able to take off and land in smaller areas. Helicopters are particularly useful in missions, including search and rescue (SAR), Air Ambulance, fire-fighting (for Fire Department), transport (e.g. crop spraying), observation (for Police and Border Guards). Frequently, performing these tasks is connected with operation in the so-called high risk areas, where an increased attention is needed because the margin for pilot error is smaller.

One of the restrictions for use of the helicopter is the Vortex Ring State (VRS) boundary. This aerodynamic phenomenon known as the VRS or “Settling with Power” is characterized by formation of circulating air stream moving along a ring shaped track around the main helicopter rotor. Conditions conducive to development of the vortex ring state occur in vertical or nearly vertical descent. The reason for creation and growth of vortex structures is balancing of rotor induced flow and stream of air flow from the bottom to the rotor. The name of this phenomenon was created by analogy to the geometry of the flow field around a rotor.

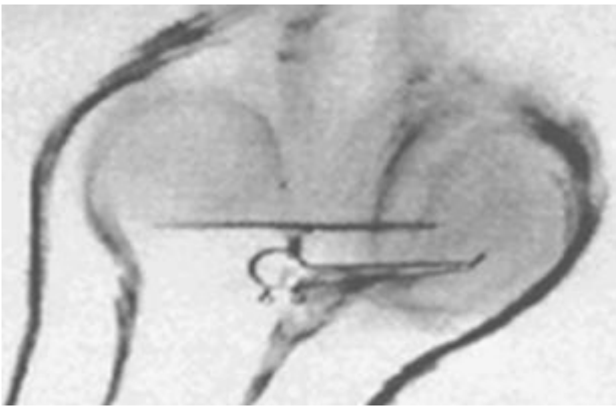


Fig.1 A visualization of the flow field around a helicopter in the VRS conditions [1].

In Figure 1. is shown a smoke flow visualization picture obtained in an flight experiment.

The phenomenon is very dangerous and can cause damage to the helicopter. The VRS causes increased levels of vibration, loss of control effectiveness, uncontrolled descent and power settling. The vortices characteristic to this phenomenon disrupt the rotor downwash thus reducing the effectiveness of its operation. This leads to a decrease in thrust and thus rapidly increasing a rate of descent. Disturbances of helicopter balance, deterioration of maneuverability and power loss are also a consequence of vortex ring. A deterioration of control properties of a helicopter is a flight safety threat especially at low altitudes.

One of the main goal of the work was a clear understanding of the dynamics of vortex ring formation process and determinants of the occurrence of vortex rings. The paper presents the results of three-dimensional aerodynamic analysis of the flow around the helicopter in the vortex ring conditions.

2. Numerical investigation of VRS

The main goal of the study is to expand knowledge about dynamics of the vortex ring structure. For a better understanding of this issue, a series of three-dimensional (*3D*) calculations were carried out using Computational Fluid Dynamics tools (CFD). The basis of this analysis was a non-stationary Navier-Stokes equations as the Reynolds averaged (RANS, Reynolds-averaged Navier-Stokes equations). The simulations have been done using geometry and performance of the W-3 "Sokol" helicopter (such as during the experiment), the model geometry is shown in the Figure 2. An analysis were performed using two computational models.

Fig.2 The helicopter W-3 "Sokol".

The first model consisted of seven components: a main rotor, a tail rotor, a fuselage, a landing gear, a tail boom, a tail skid, a synchronized elevator (Figure 3). The helicopter main rotor was modeled using a constant pressure jump over the disc (fan model). The grid was generated by ICEM CFD software. The cubical domain was produced with the unstructured grid consisted of tetrahedral cells and several layers of prisms around a helicopter fuselage (Figure 4). The induced hover velocity of modeled rotor is approximately equal to v_{io} = 14.5 [m/s].

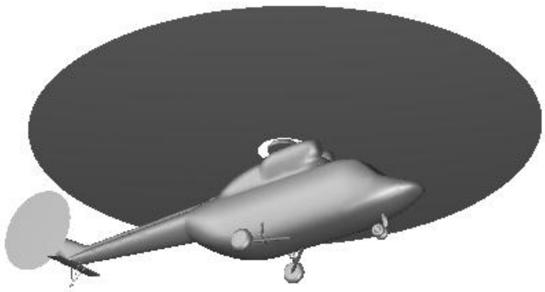


Fig.3 A computational geometry model.

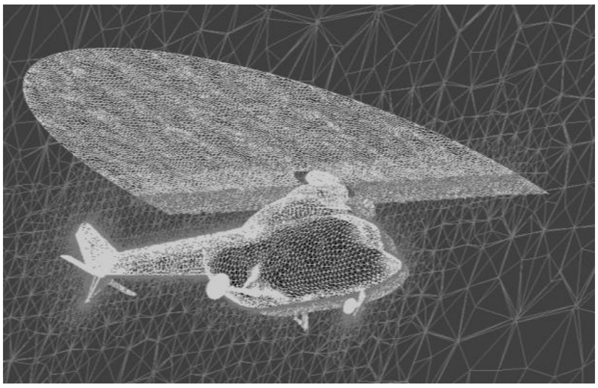


Fig.4 Structure of the grid around a helicopter.

The purpose of this study was the simulation of the helicopter flight maneuver in the vicinity and inside the zone of VRS occurrence. The analysis was performed using on measured flight test data W-3 helicopter. The maneuver of descent with a change of horizontal component of the velocity over the time was performed. The helicopter movement was carried out using the User Defined Function (UDF) in FLUENT. The maneuver began with a vertical speed of descent w = -7.6 [m / s] and the forward speed v = 4.2 [m / s]. The last maneuver lasted 40 s and during occurred continuous change both velocity components. The figure 5 is the velocities versus time graph. Velocities have been recorded in the course of experimental test flights recorded during investigation of the vortex ring state (in Poland at 2009 year).

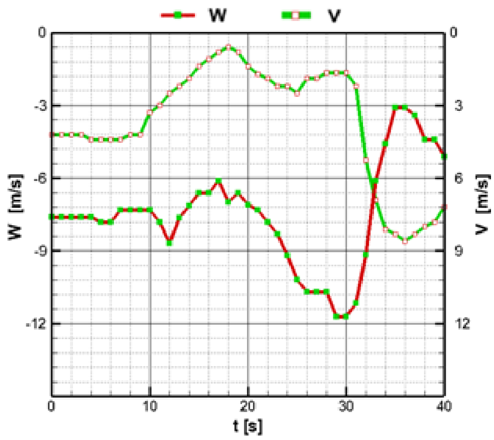


Fig.5 A velocity components versus time graph.

A simulation of maneuver is an attempt to reproduce the helicopter flight based on the records from the on-board recording devices. Intense flow disturbances around a helicopter observed during this flight. Velocity pathlines near the helicopter during maneuver (w=7.6 [m/s], v=4.2 [m/s].) is presented in the following Figure 6.

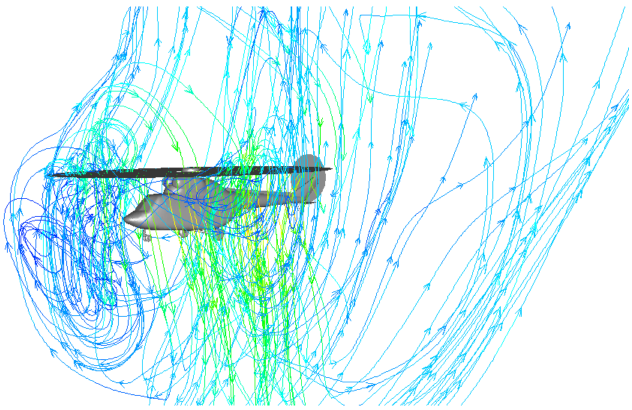
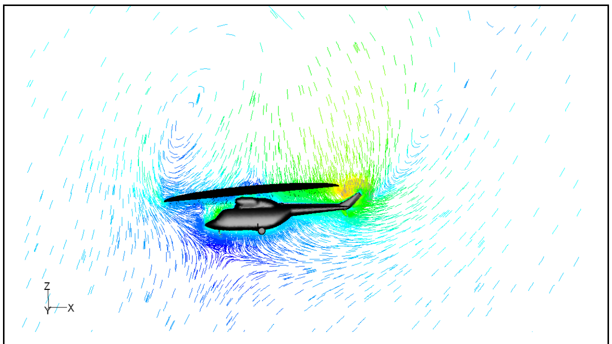
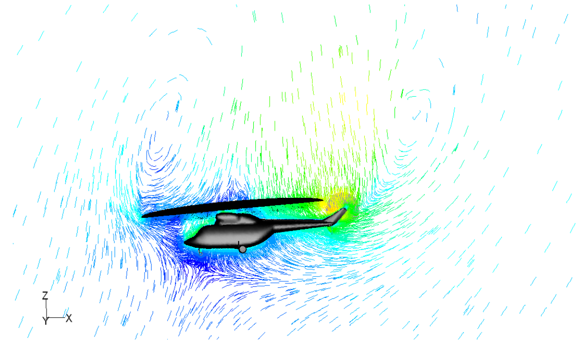


Fig.6 The visualization of flow field in the start case of the maneuver.

Table 1. A visualization of the maneuver.



29s



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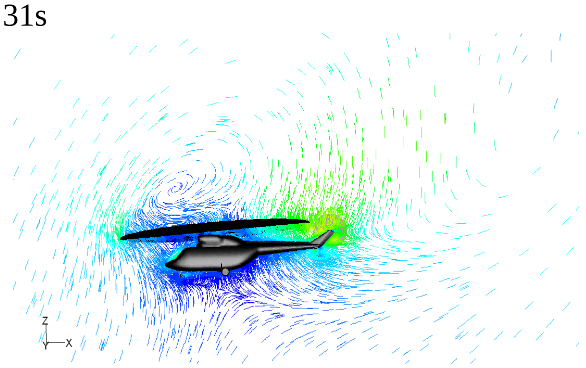
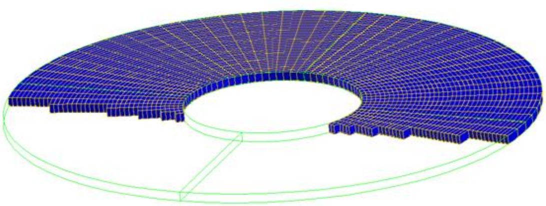


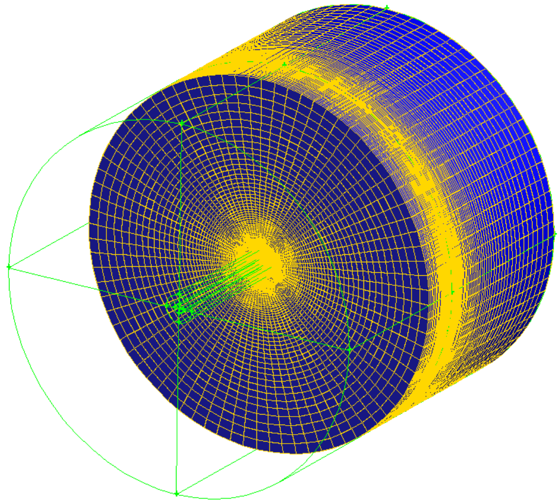
34s

The most interesting was the part of flight at minimum forward speed and maximum rate of descent. The results of calculations of middle and last part of the maneuver (as a velocity visualization) are presented in the table 1. The flow around a helicopter in the start case is different than in the hover. Inflow velocity from the bottom of the rotor disk to the top is large and flow induced by a rotor is disrupts significantly. Horizontal and vertical components of the velocity changes over time led to the increased intensification of this phenomenon. Vortex structures above the rotor plane were observed in the middle part of the simulated flight. An increase of forward speed caused a blowing out the vortices.

Simulation of the isolated rotor in forward flight was the second part of the calculation. The rotor was modeled by using the Virtual Blade Model (VBM). Virtual Blade Model (available in ANSYS FLUENT software) is based on the assumption the rotor systems with momentum sources on an actuator disk. The VBM is the coupling of the Navier-Stokes equations describing the flow field computed in FLUENT with the theory element of the blade, in which the forces and moments acting on the rotor is obtained by integration of the forces and moments on the individual elements of the blade. This method does not require accurate modeling of the rotor blades geometry but allows to obtain relatively accurate results (including aerodynamic characteristics as functions of Mach and Reynolds number for all using airfoils, number of blades, rotor radius, pitch-flap coupling, blade mass, rotor speed, tip effect). Due to the relatively short time of calculations and the accuracy of the results this model gives the possibility to simulate helicopter movement in any direction (simulations of the axial and non-axial descent and selected helicopter maneuver). The computational grid is shown in figure 7. An analysis using the VBM model concerned the prediction of air flow around a rotor for various flight condition. The calculations were performed for velocities from 0 to 20 [m/s] and two pitch angle settings.



a)



b)

Fig.7 Grid of a rotor using in a Virtual Blade Model.

The results from computational study of fluid flow around a isolated rotor were presented in Figures 8 and 9. For analysis was selected two pitch angles: φ=12º and φ=15º. Visualization of pathlines colored by velocity magnitude shown below.

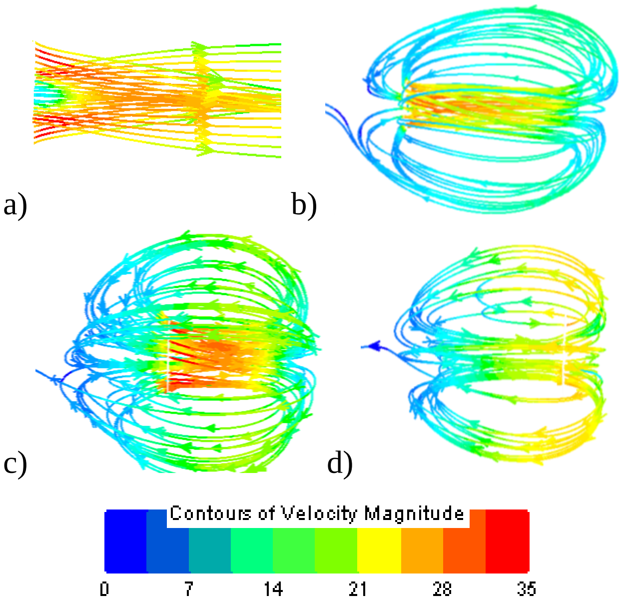


Fig.8 Flow field around the rotor: a) V=0 m/s, φ=15°; b) V=10 m/s, φ=15°; c) V=15 m/s, φ=15°; d) V=20 m/s, φ=15°.

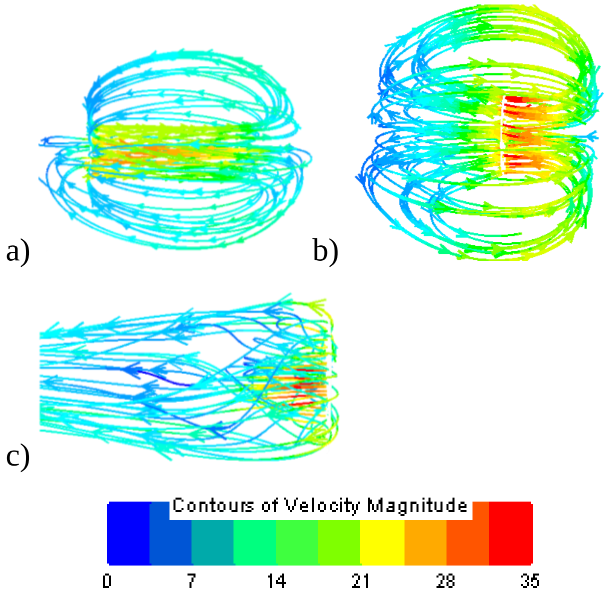


Fig.9 Flow field around the rotor:
a) V=10 m/s, φ=12°; b) V=15 m/s, φ=12°;
c) V=20 m/s, φ=12°

Fig.10 The model of a helicopter used in a wind tunnel test.

A character flow field near the rotor shown in figures. Increasing the inflow velocity on the rotor from 0 to 20 [m /s] causes a gradual growth of the ring vortices.

3. Experimental study

Experimental tests with exceeding the limits prescribed for the particular aircraft are performed in order to explain and justify the causes of these exceedances that can affect the ability to return to safe state.
Study the dynamics of vortex ring was also carried out by experimental investigation. Studies were performed using a helicopter model (diameter rotor D=0.688 [m]) in the wind tunnel of the Institute of Aviation. An image of the helicopter shown in a Figure 10. One of the most important and valuable part of experiment was the attempt to visualize the flow field around a model helicopter. This was carried out by the use of smoke generators. The resulting image is shown in Figure 11. Images of air flow shown for the one selected value of velocity inflow to the rotor.

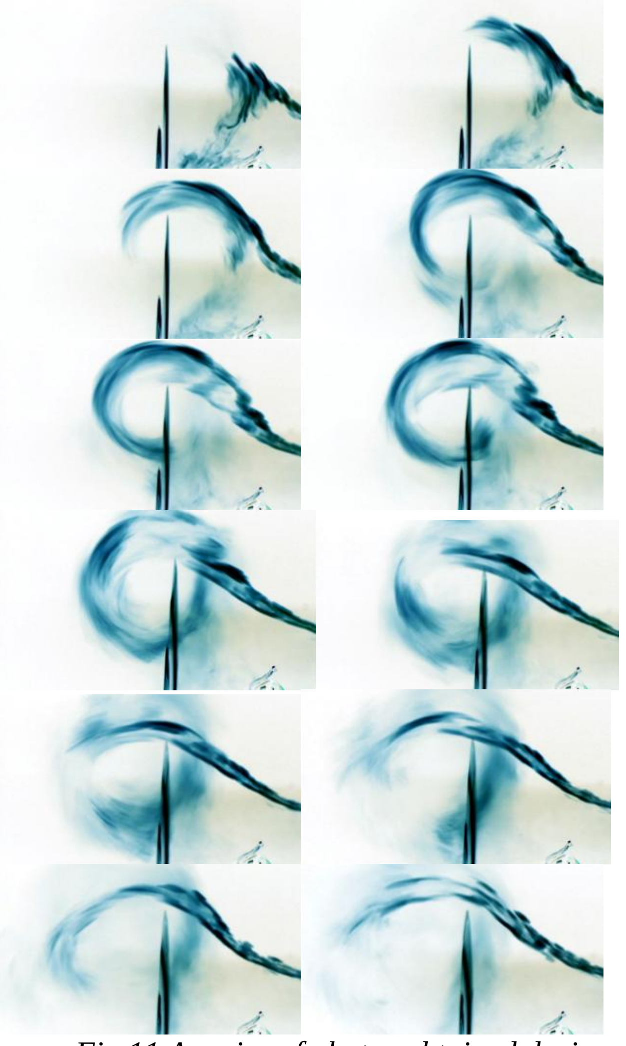


Fig.11 A series of photos obtained during wind tunnel test

4. Conclusions

In the recent years, the use of helicopters increased. Determination of limits on the use provides acceptable levels of safety. One of the restrictions for use of the helicopter is the vortex ring state boundary. Research on the issue of the VRS are intended to increase the safety and reliability of helicopters. The results of experimental and numerical analyzes show that the real area of the occurrence of VRS can be a little different than the theoretical area (the VRS develops in some cases earlier and can take longer than in the theoretical). This paper presented the computational model validated with experimental data. The results are provided an indication of the extended and closeness to the boundaries of flight.

5. Future work

The calculation results presented in this paper are part of the work carried out on the phenomenon of the vortex ring state on the helicopter. Based on previous calculations performed the analysis of parameters, such as velocity induced by the rotor, power, thrust and pitch angle for axial flow [6]. Numerical analysis of the tail rotor vortex ring state also performed [7]. Numerical analysis of the tail rotor vortex ring state performed (hover helicopter in cross winds and rotation the helicopter around the vertical axis). Currently the wind tunnel measurements associated with the VRS is also carried. In the future computational model will be developed (it will be using Blade Element Theory methods) and it will validating with the experimental results.

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