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STUDY ON THE EFFECT OF THE DESCENT RATE OF A HELICOPTER IN THE VORTEX RING CONDITIONS

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Abstract

One of the limiting factors for a helicopter operation is the Vortex Ring State (VRS). This aerodynamic phenomenon, known as the VRS or "Settling with Power", is characterized by the formation of circulating air stream moving along a ring shaped track around the main rotor of a helicopter. Conditions, conducive to development of the vortex ring state, occur in the vertical or nearly vertical descent. This leads to decrease in thrust and thus rapidly increasing the rate of descent. This phenomenon occurs for an appropriate combination of induced velocity and the velocity of the stream of airflow from the bottom to the rotor. The rates of change of velocities delimit dangerous areas of flight.

The objective of this work was to investigate the influence of the descent rate of a helicopter on the vortex ring formation process and determinants of the occurrence of vortex rings. For better understanding of the nature of this state, a computational method was applied. Series of three-dimensional (*3D*) unsteady *analysis was carried out using Computational Fluid Dynamics tools (CFD). Simulations were realized using geometry and performance of the W-3 "Sokol" helicopter. The paper presents results of a helicopter operation in axial and non-axial descent conditions. Three calculation cases of vertical flight of a helicopter with different rates of velocity changes were considered. A simulation of non-axial descent was based on the measured flight test data for the W-3 helicopter. The results provide information about the changing nature of the flow in the course of the movement of a helicopter and show the influence of the rate of descent during initiation on the development of VRS. Results of the calculations provide guidelines for helicopter pilots.*

***Keywords**: Vortex Ring State, helicopter descent, computational fluid dynamics, flow simulations*

1. Introduction

Recently the exploitation of helicopters has increased significantly. Their advantage over other aircraft is the ability to perform flights in each direction, at low altitude and low speed and the ability for hover. Helicopter and any other aircraft flight techniques must be very safe. Improving operational safety is ensured by defining flight rules as the boundaries of acceptable use. They are based on a combination of flight parameters, which can set safe and potentially dangerous areas of flight. One of the limiting factors for a helicopter operation is the Vortex Ring State. The Vortex Ring State [2, 3, 5], known as the VRS or "Settling with Power", occurs in the vertical or nearly vertical descent. The reason for creation and growth of vortex structures is balancing of the rotor induced flow and the stream of airflow from the bottom to the rotor. VRS is a very dangerous phenomenon, which may cause the damage of a helicopter.

The objective of this work was to investigate the influence of the descent rate of a helicopter during its formation process and determinants of the occurrence of vortex rings. For better understanding of the nature of this state, the computational method was applied. The paper presents results of a helicopter operation in axial and non-axial descent conditions. Series of three-dimensional (*3D*) calculations were carried out using Computational Fluid Dynamics tools (CFD). The basis for this analysis was the application of non-stationary Navier-Stokes equations as the Reynolds averaged (RANS, Reynolds-averaged Navier-Stokes equations). Simulations were realized using geometry and performance of the W-3 "Sokol" helicopter.

2. Boundaries for low speed helicopter flight

Restrictions for the use of the aircraft to enhance safety depend on several groups of factors related to flight conditions, environmental conditions or helicopter structure (range limits for individual components). Helicopter flight technique particularly determines the existence of combination of height-velocity, which should be avoided for safety. The H-V diagram [4, 6] provides information on this subject. The H-V zones are also known as the dead man's curves and define the range of potentially dangerous values of flight velocity and height. The correct reaction and increased attention by a flight crew are required in this condition because the margin for error is smaller. Dangerous areas within the H-V curve are particularly important in low-speed and low-altitude flight operations. Performance tasks in that range are the biggest advantage of helicopters. Helicopters are particularly useful in missions, including search and rescue (SAR), fire fighting, transport, observation. It is, therefore, necessary for operating in such conditions. On the diagram H-V, there is a primarily specified zone of low speed and altitude (as the dangerous area above specified primarily a zone of low speed and low altitude). Another restriction on low speed flight, which is used in helicopter operations, is a polar curve of helicopter descent with the vortex ring state boundary. A three-dimensional velocity diagram (w – vertical velocity, v – horizontal velocity, u – side velocity) with the shaded area is given in Fig. 1.

An aerodynamic phenomenon known as vortex ring state (VRS) is characterized by the formation of a circulating air stream moving along a ring shaped track around the main rotor of a helicopter. It is assumed that the theoretical range of the occurrence of VRS is $w = (0.5 - 1.5)\, v_{io}$, where: v_{io} – induced velocity for the rotor in hover. Practically, this phenomenon occurs most often during the vertical descent, but it can occur also in hover or climb (in a strong vertical wind gust) [3].

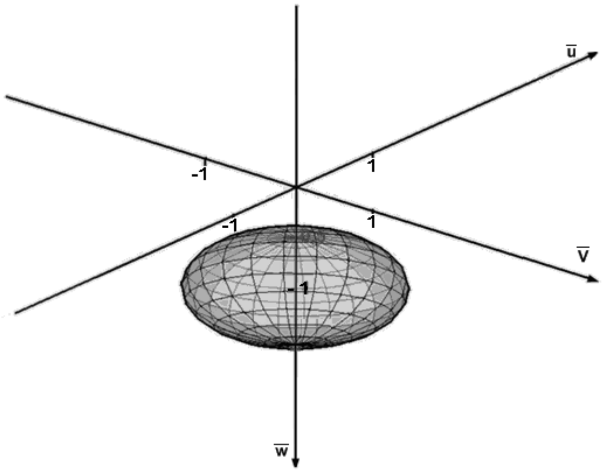


Fig. 1. Three-dimensional theoretical area of VRS [1]

The name of this phenomenon was created by analogy to the geometry of the flow field around a rotor. These specific vortices disrupt the rotor downwash, thus reducing the efficiency of its operation. This leads to decrease in thrust, and thus rapidly increasing the rate of descent. The disturbance of the balance, deteriorated helicopter manoeuvrability, power loss and increased levels of vibration are also consequences of vortex ring.

3. Numerical investigation of the Vortex Ring State

The purpose of the numerical analysis was to simulate the helicopter flight manoeuvres close to the boundary of the vortex ring state region and to evaluate the influence of a descent rate on the VRS occurrence. The calculations were based on the ANSYS FLUENT code. In the simulations a three-dimensional, unsteady-state solver was applied. The flow field was calculated using the Spalart – Allmaras one-equation model for turbulent viscosity. Two cases were considered: the axial and non-axial descent. In both cases, the numerical investigation was conducted using the geometry and performance data of a helicopter W-3 „Sokół" (a gross weight $m=6400\ kg$, a main rotor radius $R=7.85\ m$, an induced velocity at hover $v_{io}=14.56\ m/s$). The geometric model of a helicopter consisted of seven components: main rotor, tail rotor, fuselage, landing gear, tail boom, tail skid, synchronized elevator (Fig. 2). The main rotor was modelled as a constant pressure jump at the disc equal to $\Delta p \approx 300Pa$.

Fig. 2. The computational geometry model

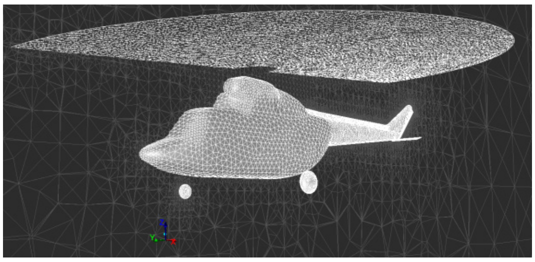


Fig. 3. The structure of a mesh around a helicopter

Any modifications to the geometric model and computational grid were made using the ICEM CFD software. The structure of mesh on the surface and in the vicinity of a helicopter is shown in Fig. 3. A computational domain is a cuboid (a grid size: *80 x 80 x 90 m*) consisting of tetrahedral elements. The helicopter movements were carried out using the User Defined Function (UDF) in ANSYS FLUENT. The simulation of the non-axial descent manoeuvre was the first of the calculations. The descent flight with a change of horizontal and vertical components of the velocity over the time based on the flight data recorded during the experimental flight test in Poland (at 2009 year). Changes of both velocities (a forward speed *v* and a vertical speed of descent *w*) over the course of time are shown in Fig. 4.

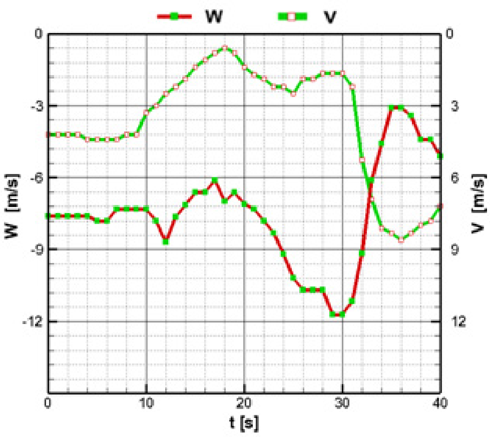


Fig. 4. Velocity components versus time graph in non-axial descending flight

In this case, the results obtained by CFD calculations can be compared with the records of a helicopter vibrations measured and registered during the flight tests. Increased levels of vibration were recorded in the zone of the VRS occurrence.

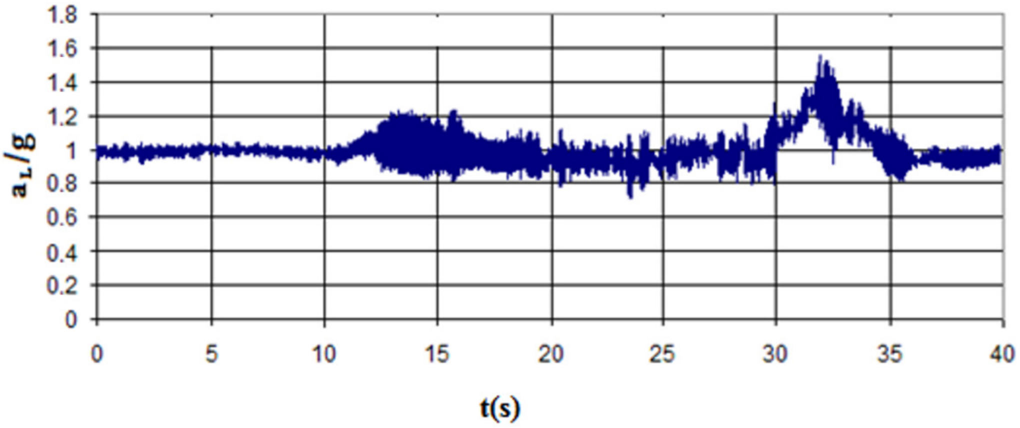


Fig. 5. An acceleration versus time graph

The main goal of this study was to investigate the effect of the descent rate of a helicopter on the occurrence of the vortex ring state (VRS). An attempt to evaluate how the VRS phenomenon depends on the descent gradient was realized by modelling a series of descents at a definite rate. In all case studies, the value of vertical speed did not exceed *20 m/s*. Increasing or decreasing the rate of descent of a helicopter during manoeuvres was defined using UDF. The relation between vertical velocity and time for different variants of the descending manoeuvre are shown in Fig. 6.

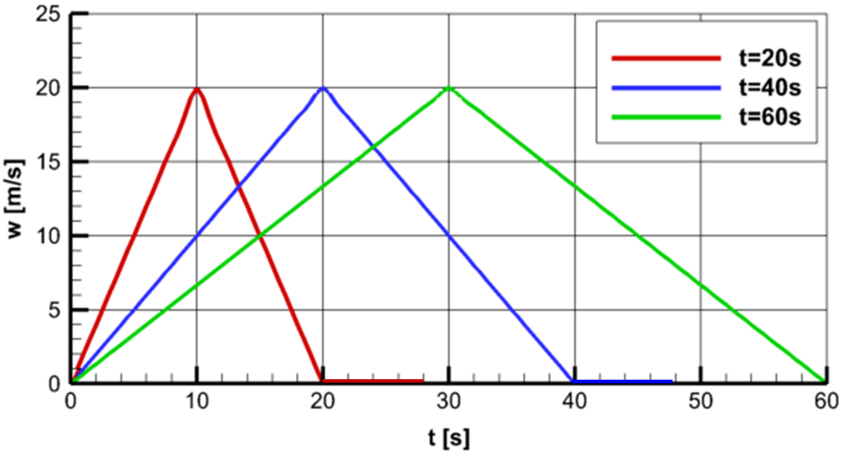


Fig. 6. Vertical velocity versus time graph in three variants of an axial descent

All helicopter manoeuvres (axial and non-axial) were simulated in the vicinity and inside the zone of VRS occurrence as is illustrated by following graphs (Fig. 7). The shaded area on plots represents the dangerous region of the VRS phenomenon.

4. Results and conclusions

The results of three-dimensional calculations of the vortex ring state presented in this paper provided qualitative information on the flow field around the helicopter and the effect of the rate descent on the intensity of the VRS. The manoeuvre of a non-axial descent is the attempt to reproduce the helicopter flight based on the records from the on-board recording devices. The simulation was started with vertical velocity *w=7.6 m/s* and forward speed *v=4.2 m/s*. The duration of the manoeuvre was *40 s*. Velocity path lines around a helicopter in the start case are shown in Fig. 8.

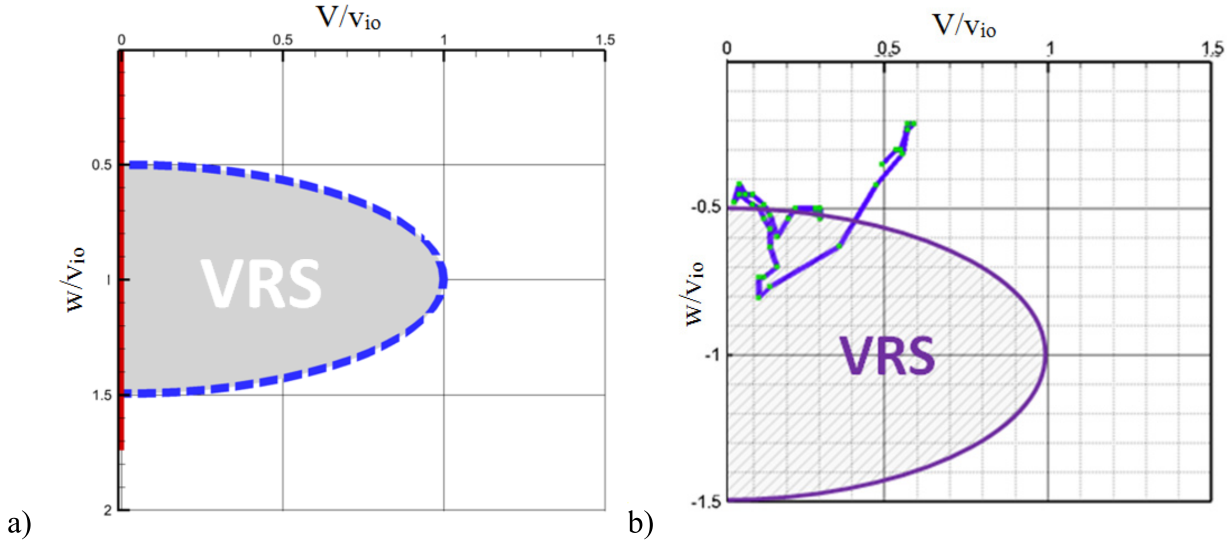


Fig. 7. Dimensionless graph for vertical velocity versus horizontal speed an axial descent; b) a non-axial descent

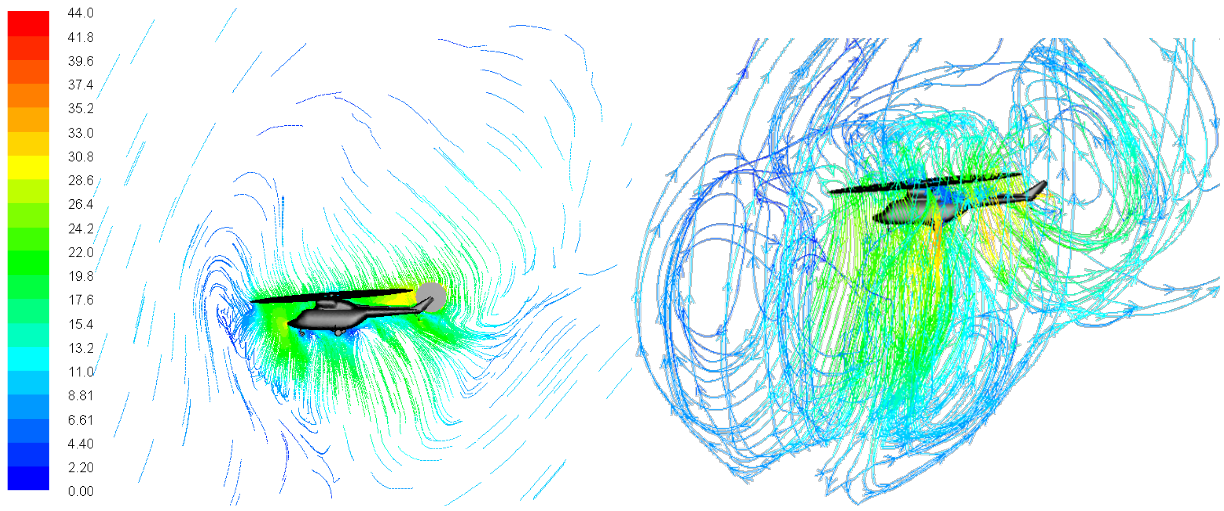


Fig. 8. The flow visualization in the start case (w=7.6 m/s; v=4.2 m/s) of a non-axial descent

The results of the calculations (as velocity visualization) are presented in Fig. 9. For developing vortex flows around the main rotor, the part of flight at the minimum forward speed and maximum rate of descent is most interesting (the vortices accumulated in front part of a rotor). Increasing the horizontal speed and vertical velocity decrease (this is the last phase of the flight) caused the vortices blown off. Such manoeuvre (increasing the forward speed) is an effective way to escape from the zone of the vortex ring.

For the evaluation the impact of descent rate on the VRS intensity 3 variants of the vertical descent of a helicopter were simulated (duration of manoeuvres: *20 s; 40 s; 60 s*). The calculations of vertical descent maneuvers start with a hover, then the rate of descent gradually increases up to *w=20 m/s* and decelerates descent to a hover at the end. Results were analysed in terms of growth and development of vortex structures as a function of the descent velocity. Flow field patterns around a helicopter are summarized in Tab. 1 as illustrated with velocity vectors.

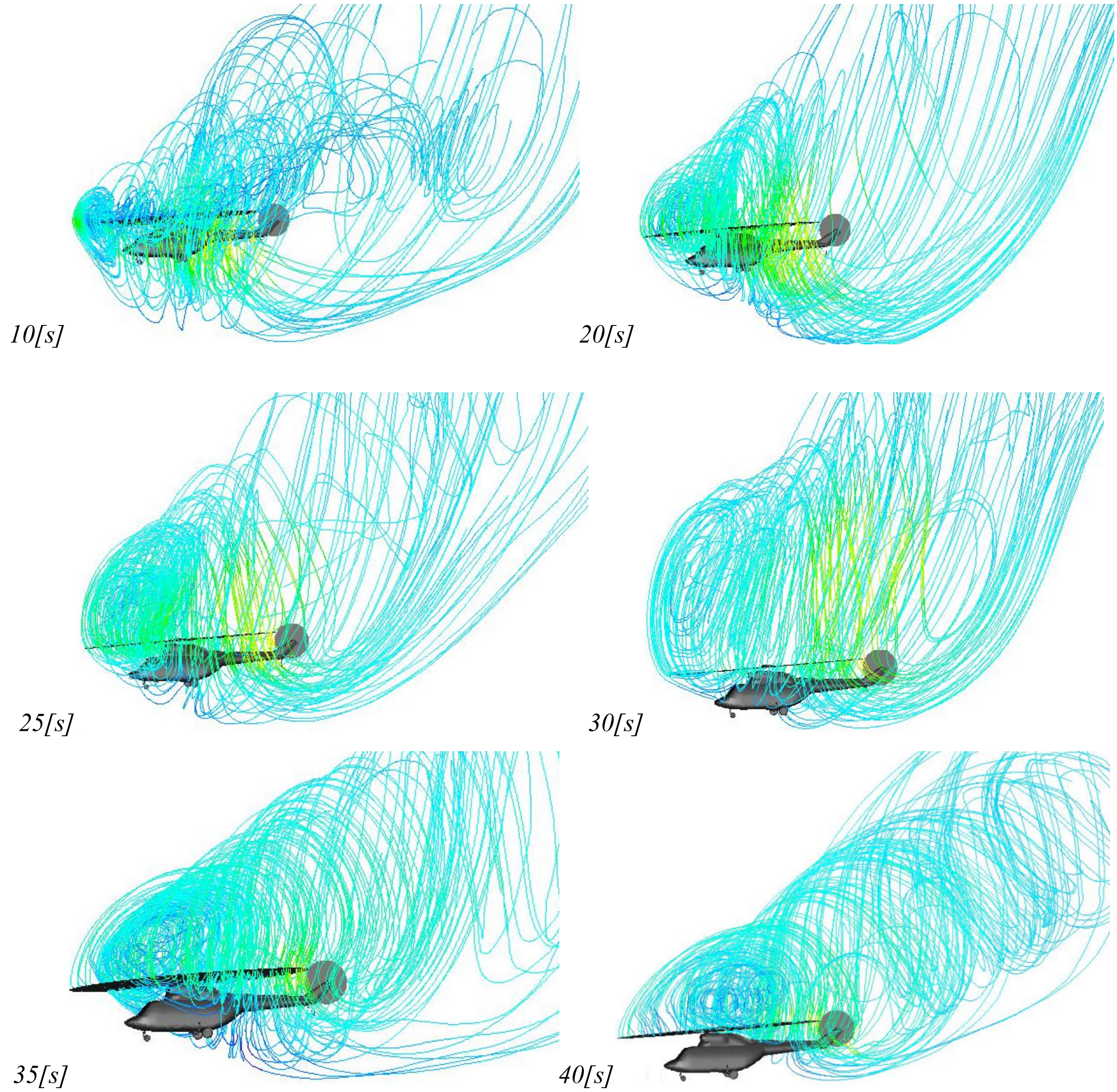
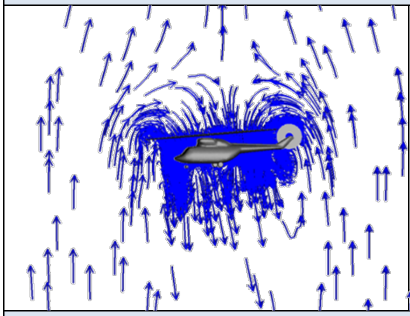
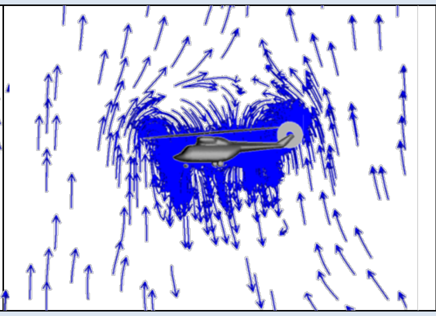
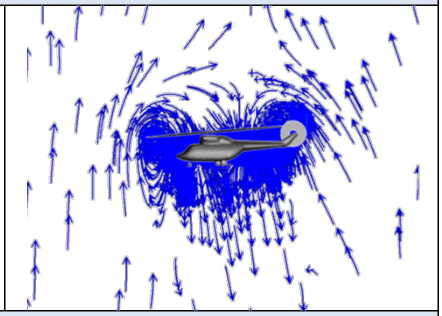
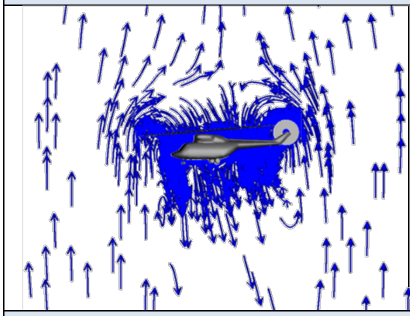
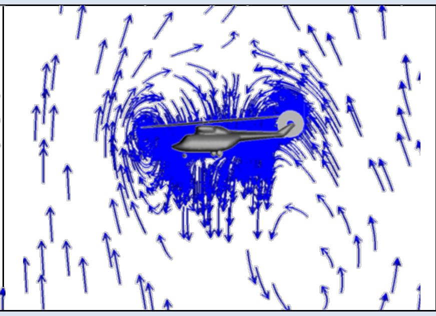
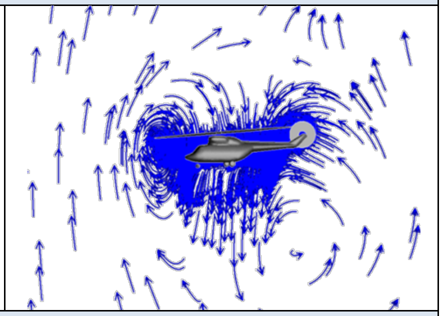
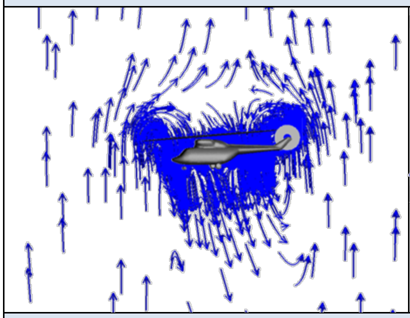
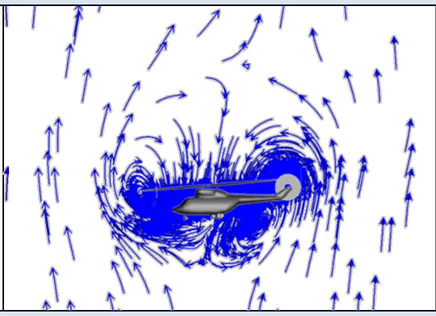
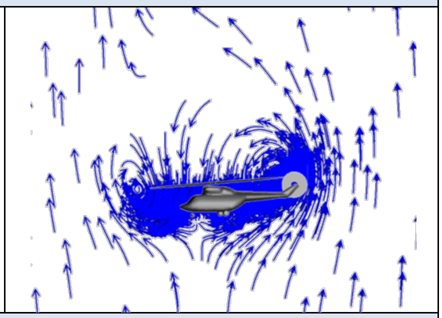
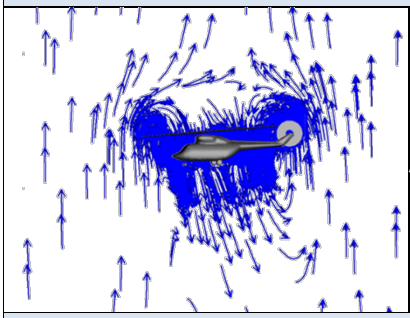
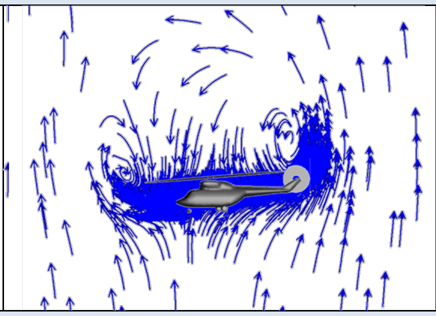
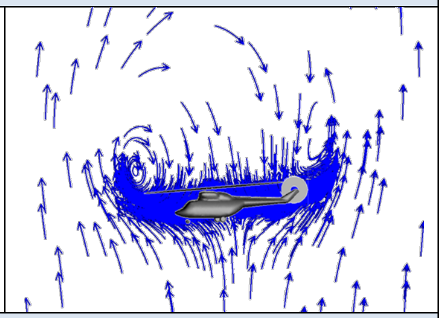
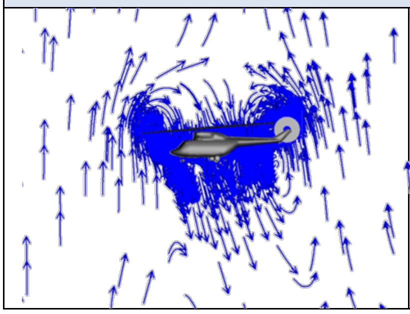
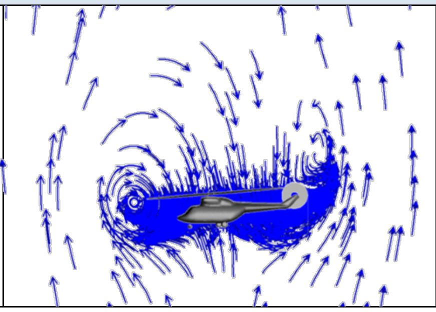
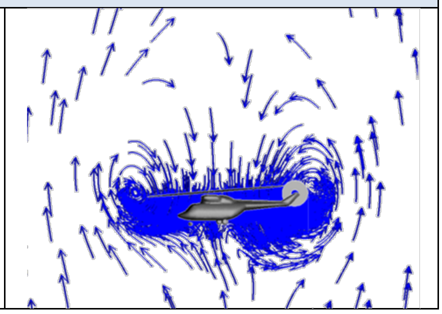


Fig. 9. A visualization of the non-axial descent

For investigated cases, images of flow field captured during the simulations are shown for the following velocity values: *10 m/s* (acceleration and deceleration), *15 m/s* (acceleration and deceleration), *20 m/s*. Comparison of flow visualization in the same vertical velocity revealed differences in the nature of flow depending on the rate of descent of a helicopter. The first manoeuvre (lasting *20 s*) is an example of the rapid descent. In this case, a fully developed form of a vortex ring was not observed. During manoeuvres lasting *40 s* and *60 s,* the vortices and vortical structures are more developed and persist much longer near a rotor than in the first case. Therefore descent with acceleration less than or equal to $1\ m/s^2$ is not recommended.

Purpose of the computational study was to simulate the helicopter flight manoeuvres in the vicinity and inside the zone of the VRS occurrence. The visualization of the flow field provided information about the influence of the rate of descent on this phenomenon. The flow images illustrated the process of the VRS formation, development and demise. Computational results proved the feasibility of presented methodology for the investigation on the issue of the VRS and also provided guidelines for helicopter pilots.

Tab. 1. A visualization of the axial descents

Manoeuvre 20s	Manoeuvre SC	Manoeuvre 60s
10 m/s acceleration		
		
15 m/s acceleration		
		
20 m/s		
		
15 m/s deceleration		
		
10 m/s deceleration		
		

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