URANS SIMULATIONS OF ON OR NEAR THE GROUND FLIGHT OF THE GYROPLANE

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Abstract

A methodology of non-real-time simulation of a rotorcraft flight has been developed and implemented in a rotorcraft engineering practice. The methodology is based on coupling of several computational models of Computational Fluid Dynamics and Flight Dynamic. The essence of the methodology consists in calculation of aerodynamic forces acting on the flying rotorcraft by solving during the simulation the Unsteady Reynolds-Averaged Navier-Stokes equations (URANS). In this approach the rotorcraft is flying inside the computational 3D mesh modelling the space filled with air. Additionally the shape of the rotorcraft and the surrounding space may change during the flight, which may result from: deflection of control surfaces, change of a main rotor pitch, approach to the ground or to a building, etc. The flight simulation procedure is completely embedded in the URANS solver ANSYS FLUENT. Flow effects caused by rotating lifting surfaces are modelled by application of developed Virtual Blade Model (VBM). In this approach real rotors are replaced by volume discs influencing the flow field similarly to real rotating blades. Time-averaged aerodynamic effects of rotating lifting surfaces are modelled using momentum source terms placed inside the volume-disc zones. The momentum sources are evaluated based on the Blade Element Theory, which associates local flow parameters in the blade sections with databases of 2D-aerodynamic characteristics of these sections (airfoils). The developed methodology was applied to simulate and analyse several stages of flight of a newly designed gyroplane. The studies described in this paper concerned mainly the flights of the gyroplane on or in direct proximity of the ground, where the ground effect significantly influences aerodynamic properties of the rotor. The paper presents the following simulations of the on-or-near-the-ground flight of the gyroplane: classic (horizontal) takeoff, vertical takeoff - similar to a helicopter takeoff, classic takeoff and "gliding" landing after simulated failure of the engine.

1. INTRODUCTION

Simulation of rotorcraft flight, especially of unsteady manoeuvre, is a very complex computational problem. Methods for solving this problem have to cope with modelling of a number of non-stationary phenomena within a range of such technical science domains as: fluid dynamics, flight dynamics, structural mechanics and fluid-structure interaction. Specific for a rotorcraft flight is the presence of two different time scales: the one associated with high-speed of rotating blades of rotors and the second, related to relatively low speed of rotorcraft flight. This makes considerable problems in integrating the equations describing a rotorcraft flight.

There is a high demand for computational methods of rotorcraft-flight simulation. At the stage of preliminary design, computational methods allow to predict behaviour of future helicopter in real flight as well as to improve its disadvantages and to optimise designed rotorcraft. Additionally, some flight conditions, particularly risky or emergency manoeuvres are rather impossible to realise in wind tunnel tests or in flight tests. In such situations, the computer simulation may be the only available research tool.

Methods for solving the complete, coupled sets of equations describing flight of rotorcraft require application of very complex computational algorithms and huge hardware resources. At the moment such approach can hardly be considered a useful tool supporting rotorcraft design process. It should be noted, however, that due to the rapid development of computer software and hardware in the near future, such methods will be increasingly developed and implemented.

On the opposite side with respect to the “exact” approach are methods based on simplified models of the rotorcraft flight. This concerns, in particular, the simplified modelling of unsteady aerodynamic phenomena. In this approach modelling an interaction between the fluid and the solid bodies (rotor blades, airframe, etc.) is most often based on the Blade-Element Theory. Such approach utilises previously prepared aerodynamic data, which are usually aerodynamic characteristics of the basic airfoils of rotor blades, the airframe, the control surfaces etc. Many computational programs based on this approach (e.g. well known popular codes:

CAMRAD[1] or FLIGHTLAB[4]) are well established in the field of computer flight simulation and Computer-Aided Design of rotorcraft.

This paper presents a method for simulating of rotorcraft flight, which can be described as an intermediate between the simplified and exact approach in respect to the exactness in modelling of unsteady fluid dynamic effects. The essence of the proposed methodology is the assumption that the flow of air around the flying rotorcraft is simulated based on complex computational model: Unsteady Reynolds-averaged Navier-Stokes (URANS) equations. These equations are solved using ANSYS FLUENT[1] solver and the whole simulation code is embedded in this solver using the additional User-Defined-Function (UDF) modules developed specially for this purpose by the author of the paper. URANS equations are solved time-step-by-step during the flight simulation, but they are integrated only with respect to the time scale associated with the movement of the whole body of the flying rotorcraft. The effect of rotating lifting surfaces and their interaction with the fluid medium is considered to be time-averaged and modelled by using the Virtual Blade Model[2] (VBM). Additional UDF modules solve equations of the rotorcraft flight dynamics and they simulate effects of moving solids in a liquid medium.

The paper presents examples of the application of the developed methodology to simulate and analyse chosen stages of flight of a newly designed gyroplane. The studies described in this paper concerned mainly flights of the gyroplane on or in direct proximity of the ground, where the ground effect significantly influences the behaviour of a rotorcraft. Classic gyroplane is a type of rotorcraft which uses an unpowered rotor in autorotation to generate lift, and an engine-powered propeller, similar to that of a fixed-wing aircraft, to provide thrust. In practice, gyroplanes are usually equipped with a mechanism enabling to use the engine for on-ground pre-rotation of the main rotor.

Schematic geometry of the gyroplane which is the subject of flight simulations described in this paper is shown in Figure 1. The gyroplane of streamlined fuselage is equipped with a two-bladed teetering rotor, three-bladed tractor-type propeller, front landing gear and v-tail which also serves as a rear landing gear.

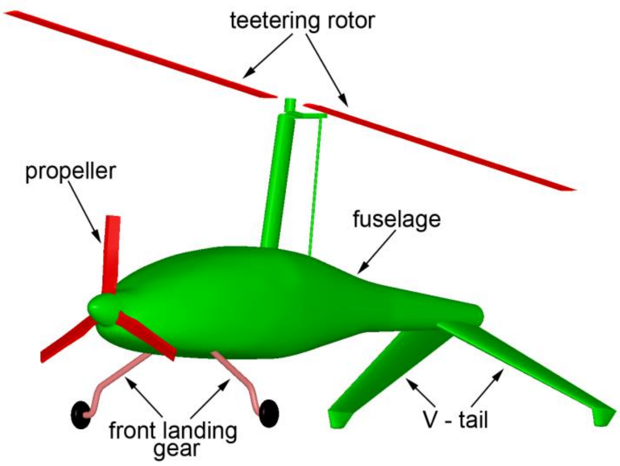

Figure 1. Schematic geometry of investigated gyroplane.

2. METHODOLOGY OF ROTORCRAFT-FLIGHT SIMULATION

The general scheme of developed methodology of rotorcraft-flight simulation is presented in Figure 2. The flight simulation procedure is completely embedded in the URANS solver ANSYS FLUENT. Flow effects caused by rotating lifting surfaces are modelled by application of the upgraded Virtual Blade Model. In this approach real rotors are replaced by volume discs influencing the flow field similarly as real rotating blades. Time-averaged aerodynamic effects of rotating lifting surfaces are modelled using momentum source terms placed inside the volume-disc zones established in regions of activity of real rotors. Such zones, replacing the real main rotor and the propeller in the case of investigated gyroplane, are shown in Figure 3. The intensities of momentum sources simulating fluidic effects caused by rotating blades are evaluated based on the Blade Element Theory (BET), which associates local flow parameters in the blade sections with databases of 2D-aerodynamic characteristics of airfoils - appropriate sections of the blade.

Compared to the original (distributed by the publisher of the ANSYS FLUENT software), the VBM module used in simulations presented in this paper has been significantly modified and expanded. The most important introduced modifications concerned:

- solving of the equations of blade flapping and coning
- modelling of a rotorcraft flight in the autorotation state

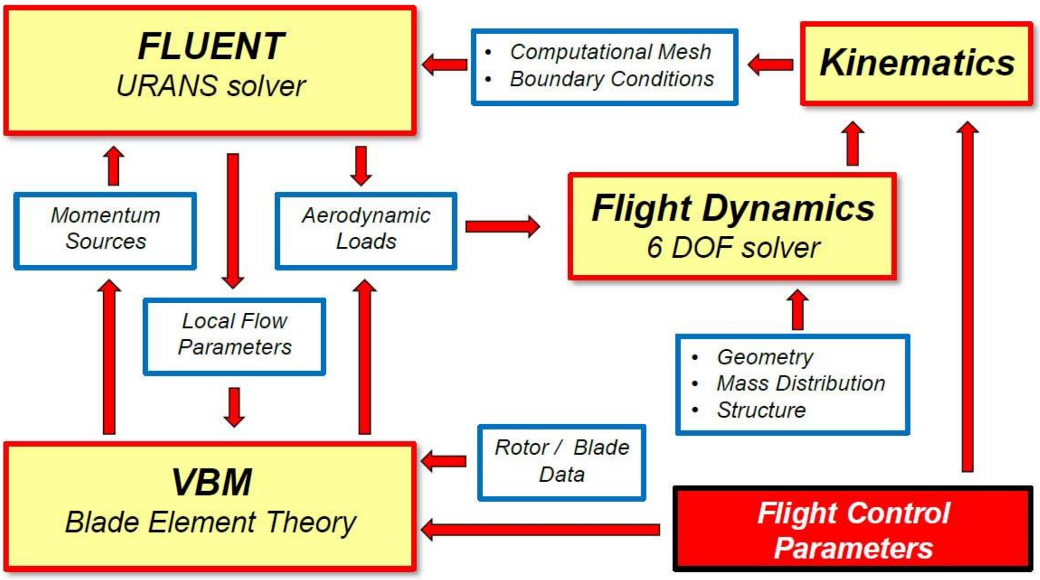

Figure 2. General scheme of the developed methodology of rotorcraft-flight simulation.

- continuous adjustment (during the flight simulation) of flight control parameters such as: collective and cyclic pitch of the rotor blades, pitch and bank angles of the rotor, rotational speed of the rotor (or propeller), deflections of the control surfaces, etc.
- continuous monitoring of local and global loads of the blades
- the possibility to take into account the aero-elastic deformations of the blades

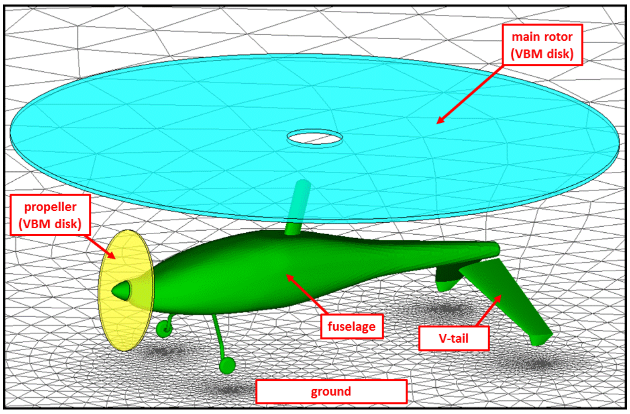

Figure 3. Computational model of the gyroplane flying in proximity of the ground.

In the presented methodology the VBM module utilises the following input data:

- geometric and mass properties of rotor and propeller and their blades
- aerodynamic characteristics of rotor/propeller-blade basic airfoils (generally as a function of angle of attack, Mach number and Reynolds number)
- rotor/propeller control parameters such as: rotational speed, pitch and bank angle, collective and cyclic pitch of the blades
- local parameters of flow in sections of rotor/propeller blades calculated by the URANS solver FLUENT

Based on these data the VBM module calculates:

- intensities of momentum sources that are used in FLUENT solver to model the flow effects of rotating blades
- global forces and moments produced by the rotor/propeller, that are used by 6 DOF solver to calculate the movement of the rotorcraft
- distribution of local loads of the rotor blades that are used by the blade-flapping-coning solver and may be used for the aero-elastic analysis

As it is shown in Figure 2, besides the essential modules FLUENT and VBM, the presented methodology utilises two additional modules.

The module FLIGHT DYNAMIC gathers the information of all momentary loads acting on the rotorcraft and solves 6-DOF equations describing a movement of the rotorcraft seen as a solid body. The rotor/propeller generated loads are obtained from the VBM module while the loads acting on the fuselage, control surfaces, landing gear, etc. are calculated by the FLUENT solver. The exemplary balance of forces acting on the gyroplane during the classic takeoff, modelled by the FLIGHT DYNAMIC module, is presented in Figure 4, where T_R – thrust of main rotor, T_P – thrust of the propeller, F_A –

aerodynamic force acting on fuselage, W – weight of gyroplane, F_W - rolling resistance force of the wheels (disappears when the wheels lose contact with the ground).

The KINEMATICS module is responsible for modelling of a movement of the rotorcraft in the space filled with the air and for the changes of gyroplane geometry. Generally it is realised by appropriate definition of boundary conditions for the FLUENT solver and by deformations of computational mesh. The latter concerns: deflections of rotorcraft control surfaces, changing a direction of the rotor rotation axis, moving away from or approaching to the solid walls (e.g. the ground, buildings, etc.). In the presented simulations the computational model of the gyroplane (see Figure 3) was developed so as to enable simulation of flight in proximity of the ground, changes of direction of the rotor rotation axis and deflections of left and right control surfaces of the V-tail. The exemplary deformations of computational mesh conducted during presented simulations may be noticed comparing Figure 5 and Figure 6. The deformations of mesh are conducted using the Dynamic Mesh (deformable mesh) technique implemented in the FLUENT solver.

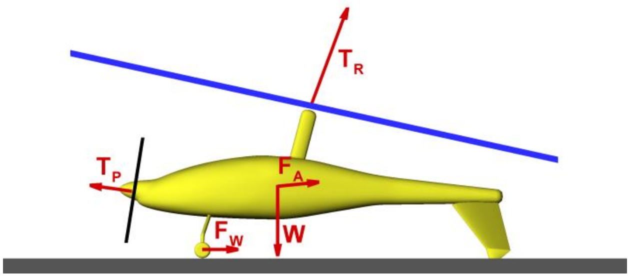

Figure 4. The balance of forces acting on the gyroplane during a classic takeoff.

3. GYROPLANE FLIGHT SIMULATIONS

The developed methodology was applied to simulate and analyse several stages of flight of a newly designed gyroplane. The studies described in this paper concerned mainly flights of the gyroplane on or in direct proximity of the ground, where the ground effect significantly influences aerodynamic properties of the gyroplane. Presented in this paper simulations of the near-the-ground flight of the gyroplane include:

- classic (horizontal) takeoff
- vertical takeoff - similar to a helicopter takeoff
- classic takeoff and emergency (gliding) landing after engine failure occurrence

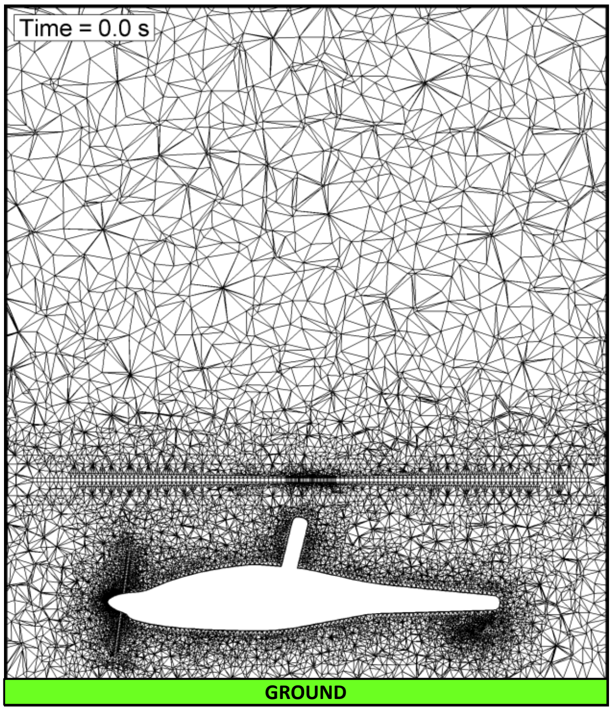

Figure 5. Initial computational mesh around the gyroplane standing on the ground.

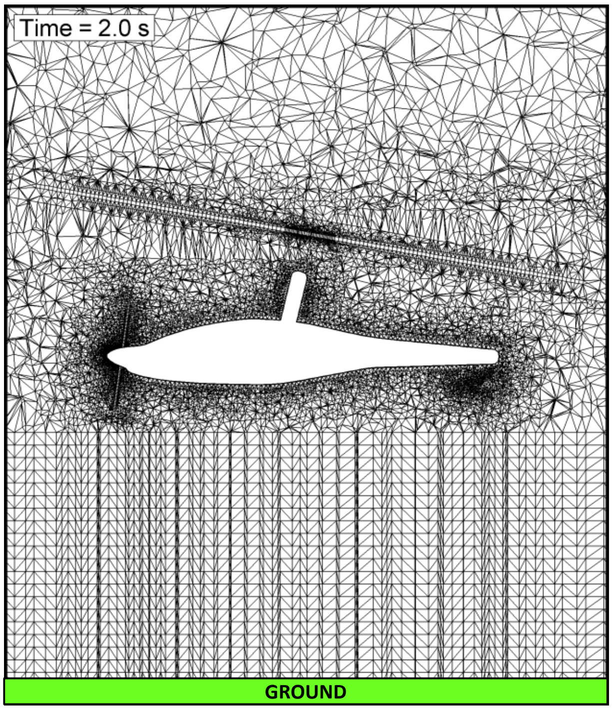

Figure 6. Computational mesh around the gyroplane with tilted backward main rotor. The gyroplane flies at low altitude above the ground.

All these simulations aimed at prediction of real-flight properties of the newly designed gyroplane in near-the-ground flight conditions. Generally, the developed methodology enables to solve 6 DOF rotorcraft dynamics. However, the presented simulations of near-the-ground flight were conducted taking into account only 3-DOF dynamics, limited to force balance and ignoring moment balance. The computational model of the gyroplane used in the simulations, shown in Figure 3, consisted of:

- fuselage with front landing gear
- main teetering rotor, modelled by VBM disk (changeable pitch the rotor, changeable collective pitch of the rotor blades)
- propeller, modelled by VBM disk (changeable thrust realised by changes of collective pitch of the propeller blades)
- v-tail (deflectable control surfaces during the flight simulation)
- the plane modelling the ground (changing its position in respect to the gyroplane during the flight)

The presented below simulations were performed without changeable deflections of control surfaces of the V-tail. The flight-control parameters taken into account in the simulations were:

- pitch angle of the main rotor (φ)
- collective pitch of the main-rotor blades (θ_R)
- collective pitch of the propeller blades (θ_P)
- rotational speed of the propeller (Ω_P) (set as zero to simulate an engine failure)

The collective pitch of the main-rotor blades was changed during the flight only during the vertical takeoff simulation. The collective pitch of the propeller blades was usually adjusted to obtain required thrust.

3.1 Classic takeoff

A classic takeoff of the gyroplane is the horizontal takeoff with a short ground run. In the beginning, the main rotor is pre-rotated. Next, due to the propeller thrust the gyroplane starts accelerated movement on the runway. Increased velocity of the gyroplane causes increase of rotational speed of the rotor due to the autorotation phenomenon. As a result the rotor thrust increases gradually. When the thrust exceeds the gyroplane weight, this lifts off the ground.

The main purpose of the simulations was to determine a strategy of the takeoff performance with possibly the shortest ground run. Generally the strategy concerned a speed and range of changes of the rotor pitch angle (φ_R) during the takeoff. The optimised strategy is presented in Figure 7 and Figure 8. Two parameters presented in Figure 8 should have been optimised: t_e - the time period of changes of rotor pitch angle and its final value φ_{Re}.

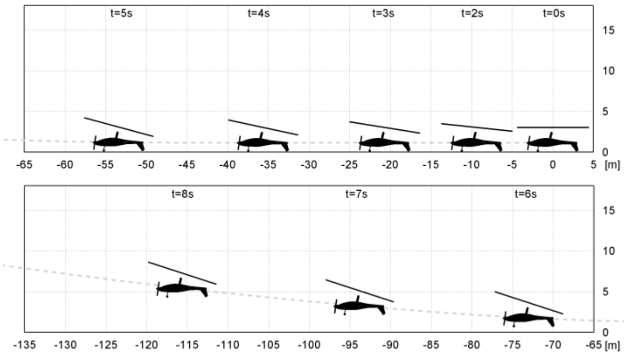

Figure 7. Assumed strategy of rotor-pitch changes during a classic takeoff.

As an example of results of conducted simulations of the gyroplane short takeoff, the dependency of the ground-run distance L_R as a function of t_e (the time period of changes of rotor pitch angle φ_R from 0deg to φ_{Re}) is presented in Figure 9. The result concerns the fixed value of $\varphi_{Re} = 20$deg. In this case the optimal time period t_e is approximately $t_e = 7.5$s.

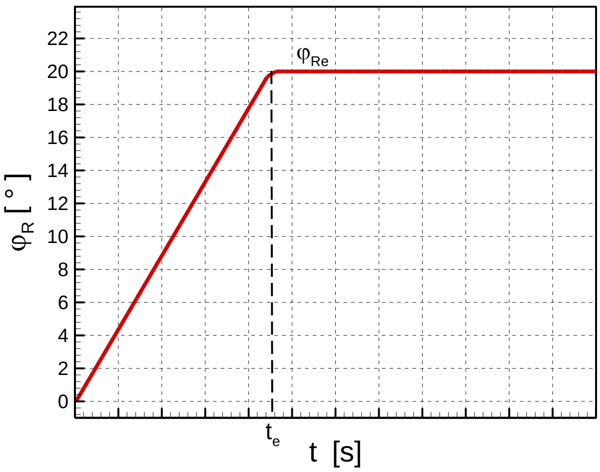

Figure 8. Optimised strategy of changes of rotor pitch angle φ_R as a function of time (t), during a classic takeoff.

Figure 13 shows flow-velocity contours in the plane of symmetry of the gyroplane in selected moments of flight, during the exemplary simulation of short takeoff. Drawings highlight the strong complexity of the air flow around the gyroplane, particularly during the initial phase of takeoff. It is worth to notice, that air-flow velocity disappears far away from the gyroplane, because in the presented approach the gyroplane flies in motionless air.

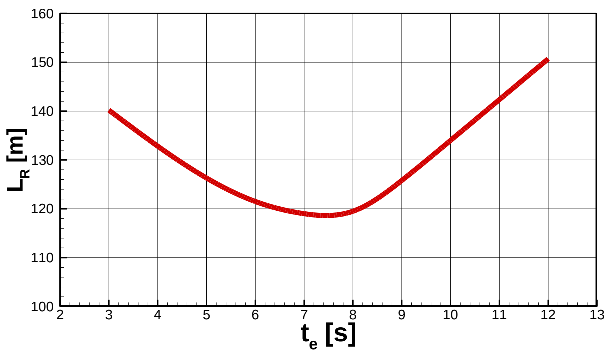

Figure 9. The ground-run distance L_R as a function of t_e – the time period of changes of rotor pitch angle from 0deg to φ_{Re} =20deg.

3.2 Vertical takeoff

In the case of “vertical” takeoff, the gyroplane takes off directly from the ground, without a ground-run phase. To perform this manoeuvre, the rotor head design should allow the blades to change collective pitch during the flight. In the initial, on-the-ground phase of the vertical takeoff, the main rotor is pre-rotated, by means of a removable drive. This phase aims at collecting as much as possible of the kinetic energy of the rotor. After ramping up the rotor, the drive is disconnected and the collective pitch of rotor blades is established on larger angles. The inertia-driven rotor starts to generate high thrust, which makes that the gyroplane “jumps” from the ground. At the same time the propeller thrust propels the gyroplane in the horizontal direction. In this way the gyroplane can take off without performing the ground-run phase. After disconnecting the drive, speed of the rotor gyroplane rapidly decreases, but due to the increasing effect of autorotation, the thrust generated by rotor should ensure safe passage to a steady flight.

Apart from appropriate design of the gyroplane and sufficient engine power, the safe and successful performance of “vertical” takeoff needs appropriate strategy of controlling the rotor pitch and collective pitch of rotor blades during this manoeuvre. Searching for such optimal strategy was the purpose of conducted simulations. Generally it was assumed that during the on-ground pre-rotation the rotor axis is in vertical position (φ_R =0) and during the vertical-take-off manoeuvre it is gradually changed to typical cruise-flight position. Subsequent stages of the vertical takeoff performed according this strategy are shown in Figure 10.

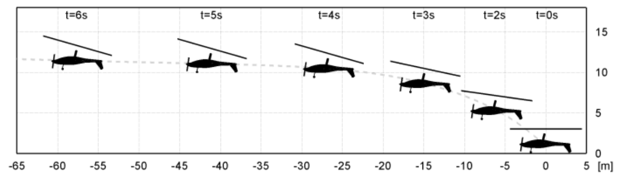

Figure 10. Subsequent stages of the simulation of vertical takeoff of the gyroplane.

Second parameter determining the successful performance of the vertical takeoff is the time-variable collective pitch of rotor blades θ_R. Exemplary, time-variable values of parameters φ_R and θ_R, that used led to a successful vertical takeoff are shown in Figure 11.

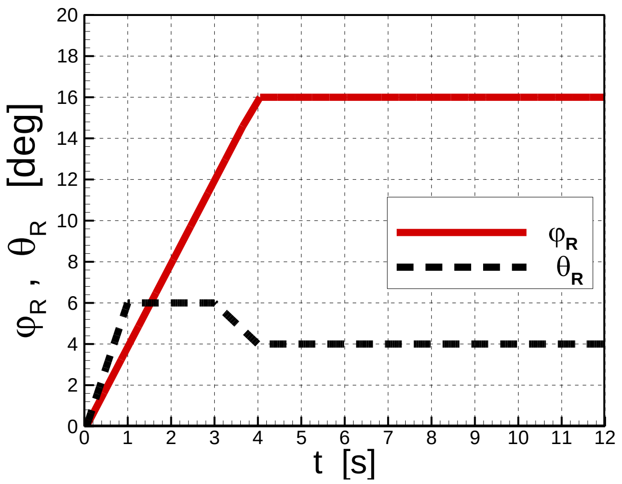

Figure 11. Example of time-variable parameters φ_R and θ_R applied in successful simulation of vertical takeoff of the gyroplane.

Selected stages of the vertical-takeoff simulation, conducted according to presented in Figure 11 strategy, are shown in Figure 14. The figure presents flow-velocity contours in the plane of symmetry of the gyroplane in selected moments of the flight.

3.3 Short flight with the engine failure occurrence

The series of emergency states of flight were simulated to predict behaviour of the gyroplane in extraordinary, off-design flight conditions. Within the range if these researches the classic takeoff and emergency (gliding) landing after occurrence of the engine failure was simulated.

In this simulation the gyroplane took off horizontally and started climbing. When it reached the altitude of 15m the engine broke down and the propeller stopped. Then the gyroplane entered a glide descent phase and in the end it landed.

The conducted simulations aimed at searching for such strategy of a gyroplane control that would give a maximal probability of safe landing. In the simulations the engine failure was modelled by stopping rotation of the propeller. Generally, the flight controls had such time dependence as shown in Figure 12. In this figure φ_{Re} is the rotor pitch optimal for the climb, while φ_{Rg} is the rotor pitch optimal for the gliding descent. Ω_P is the nominal rotational speed of the propeller and t_2 is time of an engine failure occurrence.

The performed simulations aimed at determination of the rotor pitch angle φ_{Rg} - optimal for the safe gliding descent. Figure 15 shows subsequent stages of exemplary simulation of the classic takeoff and safe, gliding landing after engine failure occurrence. In this simulation the rotor pitch angle optimal for the safe gliding descent was established φ_{Rg} = 0deg.

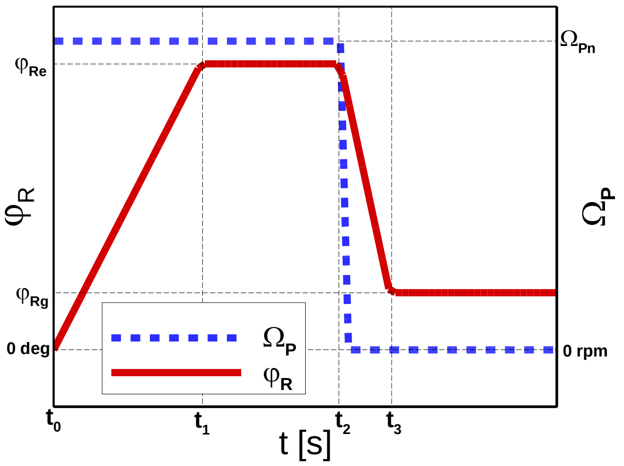

Figure 12. Changes of rotor pitch angle (φ_R) and propeller rotational speed (Ω_P) as functions of time during the short flight of the gyroplane with the engine failure occurrence.

4. CONCLUSIONS

The methodology of computational simulation of a rotorcraft flight has been developed. The methodology is based on coupled, several methods of Computational Fluid Dynamics and Flight Dynamics. The essence of the method consists in calculation of air flow around the flying rotorcraft based on solution of Unsteady Reynolds-Averaged Navier-Stokes equations that are solved using the ANSYS FLUENT solver. Time-averaged flow effects induced by rotating blades are simulated using the developed Virtual Blade Model – the UDF module extending research capabilities of the FLUENT code.

The developed methodology was applied to simulate on-or-near-the-ground flight of the newly designed gyroplane. The Dynamic Mesh technique, implemented in FLUENT solver, was applied to simulate a gyroplane flight in proximity of the ground as well as changes of the gyroplane geometry resulting from changes of a pitch of main rotor or deflections of control surfaces.

The presented examples of simulations of the gyroplane flight show research potential of the developed methodology and its possible applications in designing of new rotorcraft.

SYMBOLS

L_R	- ground-run distance
t	- time
t_e	- time of changes of φ_R from 0 to φ_{Re}
φ_R	- pitch angle of main rotor
φ_{Re}	- value of φ_R optimal for a climb
φ_{Rg}	- value of φ_R optimal for a gliding descent
θ_R	- collective pitch of main-rotor blades
Ω_P	- propeller rotational speed

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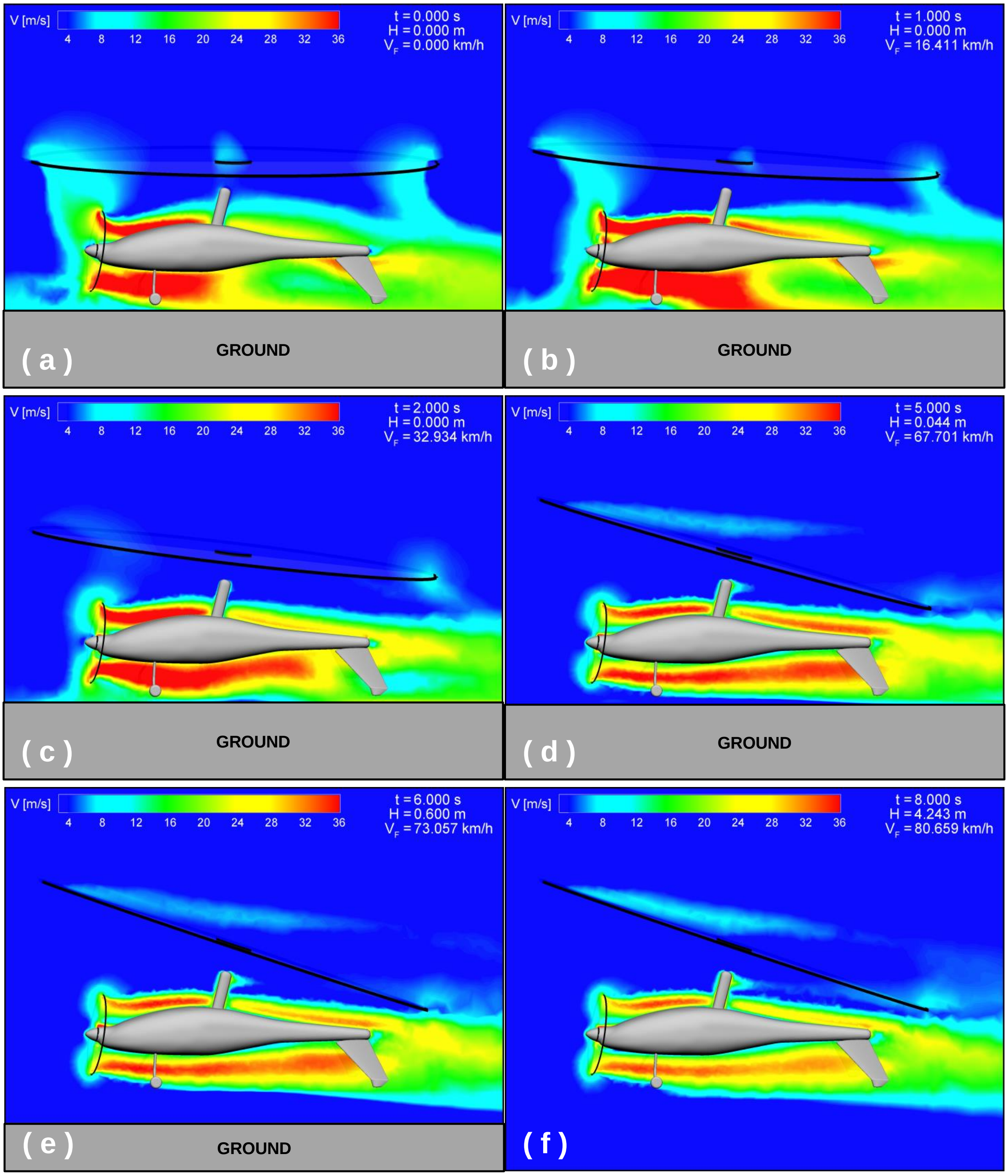

Figure 13. Air-flow-velocity contours in a plane of symmetry of the gyroplane
in selected moments of classic short takeoff.
(a) t=0s: pre-rotation of main rotor, (b) t=1s: beginning of the ground run, (c) t=2s: ground run,
(d) t=5s: off the ground, (e) t=6s: climb - altitude 0.6m, (f) t=8s: climb - altitude 4.2m

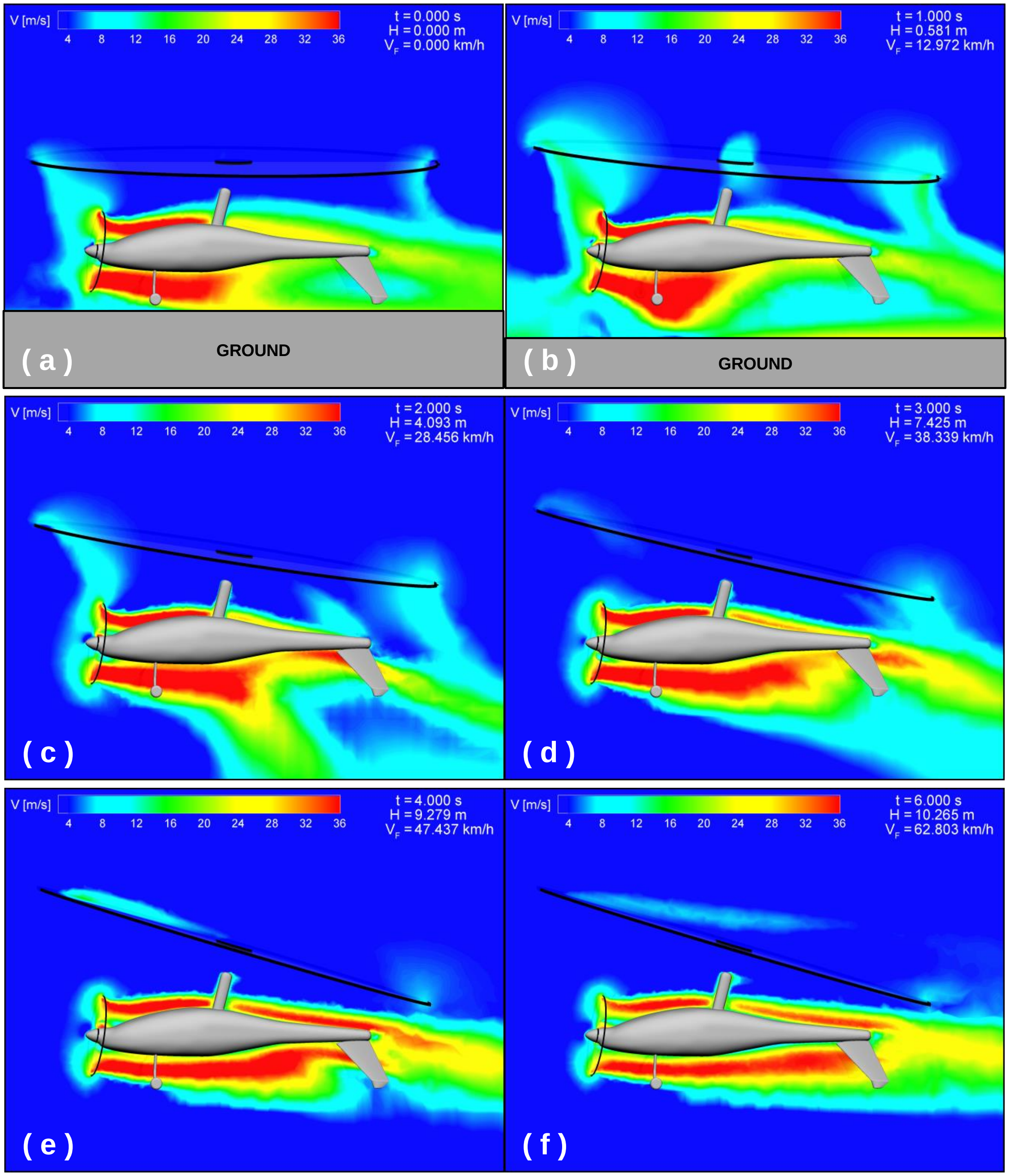

Figure 14. Air-flow-velocity contours in a plane of symmetry of the gyroplane in selected moments of vertical takeoff. (a) t=0s: on-ground pre-rotation of main rotor, (b) t=1s: initial phase of takeoff, (c) t=2s: initial phase of forward flight, (d) t=3s: forward flight with gradually decreased climb velocity, (e) t=4s: forward flight with gradually decreased climb velocity, (f) t=6s: forward flight

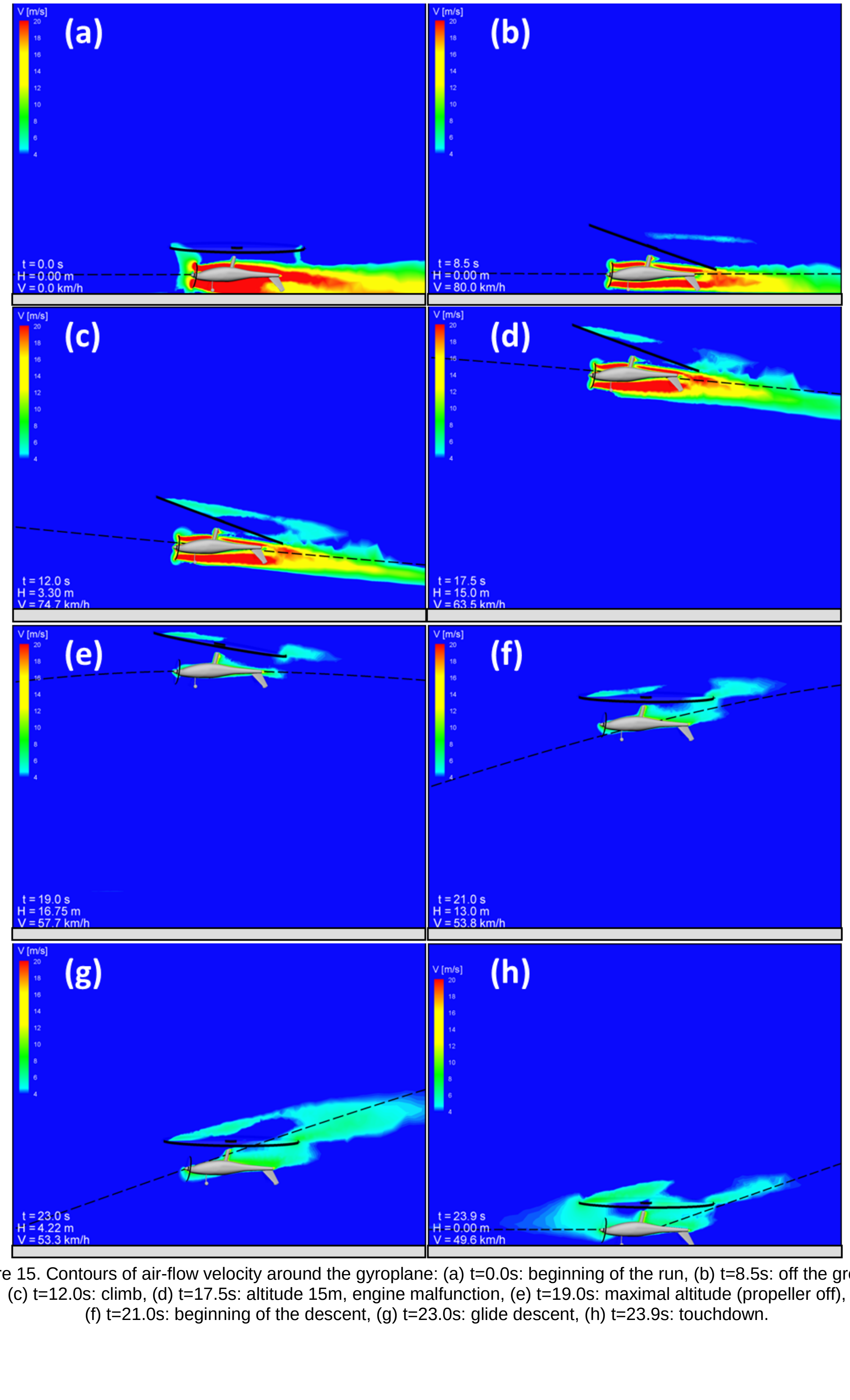

Figure 15. Contours of air-flow velocity around the gyroplane: (a) t=0.0s: beginning of the run, (b) t=8.5s: off the ground, (c) t=12.0s: climb, (d) t=17.5s: altitude 15m, engine malfunction, (e) t=19.0s: maximal altitude (propeller off), (f) t=21.0s: beginning of the descent, (g) t=23.0s: glide descent, (h) t=23.9s: touchdown.