Vortex-Ring State on a descending VTOL aircraft: aerodynamic modelling and Avoidance System

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Abstract

Rotorcraft or Vertical-Take-Off-and-Landing (VTOL) aircraft pose a series of critical operating conditions that require careful attention. Descending vertical flight is emblematic, since it may be characterised by the so-called Vortex Ring State (VRS), that causes serious safety concerns. This aerodynamic phenomenon occurs during medium speed vertical descent flight of VTOL vehicles. The relative air speed directed upwards intercepts the main rotor induced flow directed downwards and the air particles rearrange themselves into a toroidal structure called "Vortex Ring". The worst consequences occur when the "Vortex Ring" places itself on the rotor disk causing a drop of rotor thrust. Usually, this thrust drop corresponds to a peak in induced velocity that is not predictable using the classic Momentum Theory for the rotor induced velocity but it can be measured experimentally. The aim of the present paper is to develop a mathematical model of the main rotor induced flow velocity able to describe the evolution of the Vortex Ring State, which then becomes a link between the slow descent and the autorotation state. The model is used to "fly" a flight dynamics three-degrees-of-freedom helicopter model in order to create a VRS Avoidance System that can be used by the pilot. The logic behind this system is based on the use of a threshold value for the induced velocity, i.e: if the measured vertical speed is associated to a value of induced velocity above an imposed threshold, the descent is converted from the vertical to oblique flight through the activation of the cyclic pitch command using a proportional-derivative control law. This system is integrated into a rotorcraft plant to build altitude and descent rate closed loop control systems.

1 Background to the Vortex Ring State Problem

The first helicopter to be produced in series was the Sikorsky R-4 in 1941; since then, the creation of the Vortex Ring during a fast descent of the vehicle was a known phenomenon. In 1949, Professor Brotherhood exploited the aforementioned aircraft, also called Hoverfly I, to visualise the Vortex Ring in flight using a smoke generator placed on the undercarriage and a camera set on the tail. The results showed the evolution of the air flow from slow to moderate descent [1].

The rotor blade has an aerodynamic section that entails the same aerodynamic features of an airplane wing: in hovering flight, the effective angle of attack is made of the geometric angle of attack minus the zero-lift angle of attack and the induced angle of attack. The latter is given by Equation 1. The induced velocity is function of the lift coefficient which is function itself of the effective angle of attack.

$$\alpha_i = \tan^{-1}\frac{v_i}{\Omega R} \tag{1}$$

During a vertical descent, the rotor pushes the air downwards but the relative speed seen by the rotor is upwards. Therefore, the net inflow of the induced velocity and the induced angle of attack itself decreases. This leads to an increment of the effective angle of attack that causes a higher lift coefficient on the next step. Thus, also the induced velocity will raise and it reaches a maximum value when the Vortex Ring is located on the rotor plane.

The steady Momentum Theory for a single propeller in pure vertical flight with all the values adimensionalised using the induced velocity in hover is described as in Equation 2, where ν and η are respectively the induced velocity and vertical speed nondimensionalized with the induced velocity in hover. Equation 2 has three solutions visualised in Figure 1.

$$\nu^2(\nu+\eta)^2 = 1 \tag{2}$$

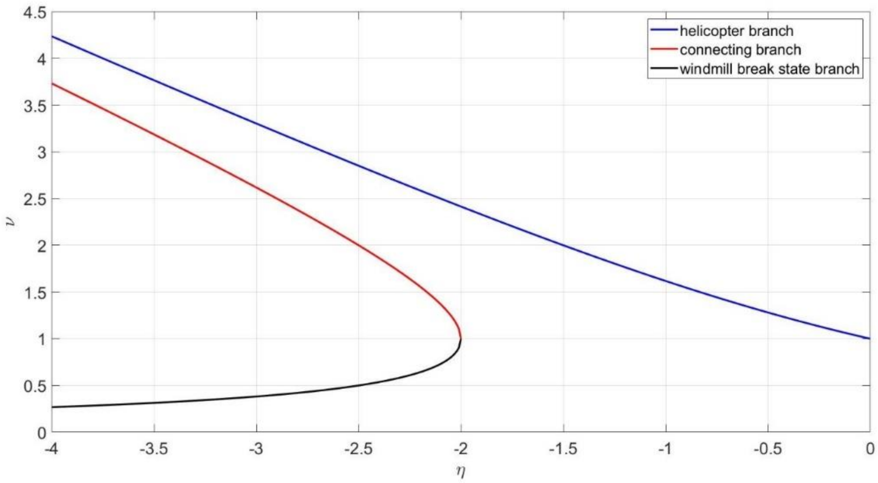

Figure 1: Momentum Theory solutions according to Eq. (2).

Castles and Gray in 1951 were the first ones to perform wind tunnel experiments on propellers to quantify the presence of the Vortex Ring State through the induced velocity. Their results (Figure 2) demonstrate the increment of the induced speed leading to a peak that occurs when the Vortex Ring is located on the rotor plane. It is also clear from the graph that the Vortex Ring State is indeed the link between the Hover point and the Windmill Brake State, also known as Autorotation, branch. The peak is set at the non-dimensional vertical speed value of -1.5 [2].

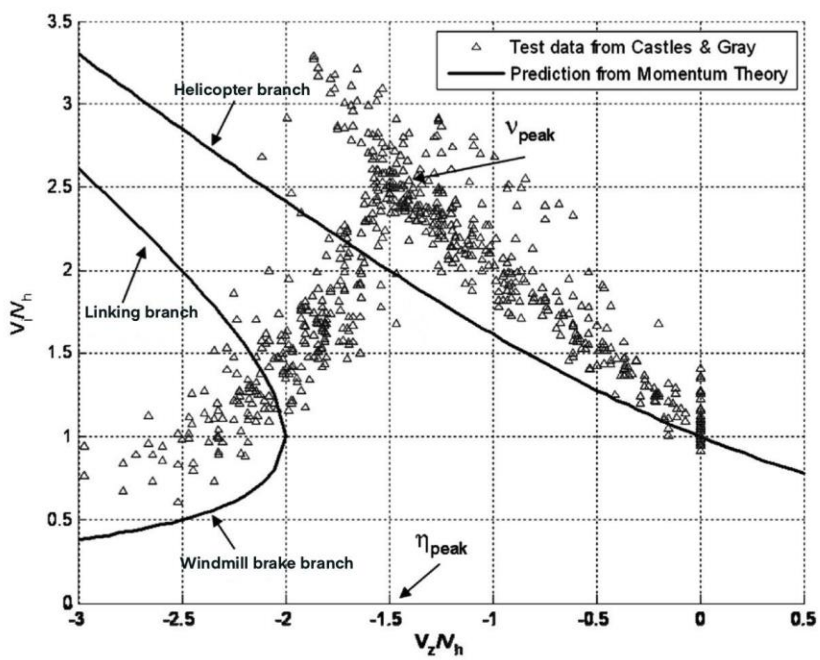

Figure 2: Castles and Gray experiments results and comparison with the Momentum Theory [2].

The vortex ring state (VRS) is named after the donut-shaped vortex ring that is visible in Figure 3.

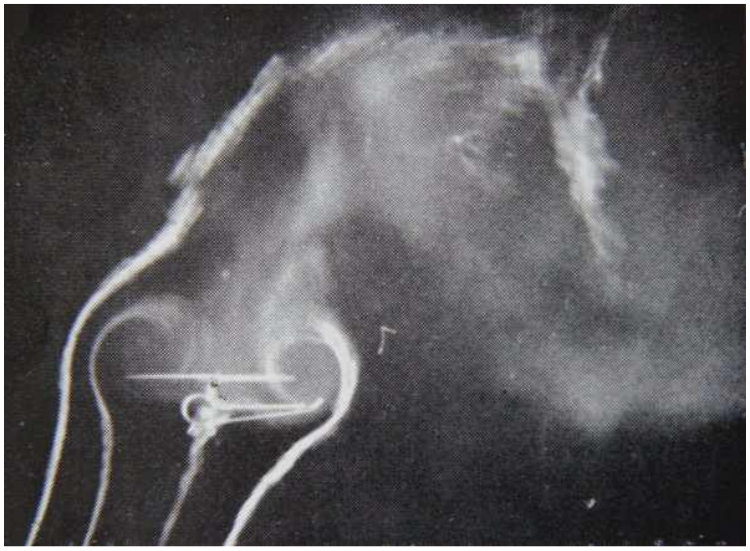

Figure 3 Smoke visualisation of helicopter rotor in vortex ring state [6]

On a helicopter main rotor, it is typically encountered when a fast descent is initiated. As the airflow around the rotor is highly turbulent in this condition, experimental data shows large fluctuations in induced velocity values as a function of climb speed (see Figure 2). A consequence of the turbulent state of the wake around the rotor are fluctuations in torque and thrust and increased levels of vibration. This would lead to pilot loss of commands control.
The ability to predict Vortex Ring State boundaries is important as it may lead to (automated) systems for VRS avoidance. Over the years, multiple criteria have been proposed to predict these boundaries, such as thrust fluctuation, torque fluctuation, heave stability and roll stability. VRS boundaries are normally displayed in a graph using normalized (by induced velocity in hover) free stream rotorcraft horizontal and vertical velocities, see Figure 4 showing the VRS boundaries from different studies.

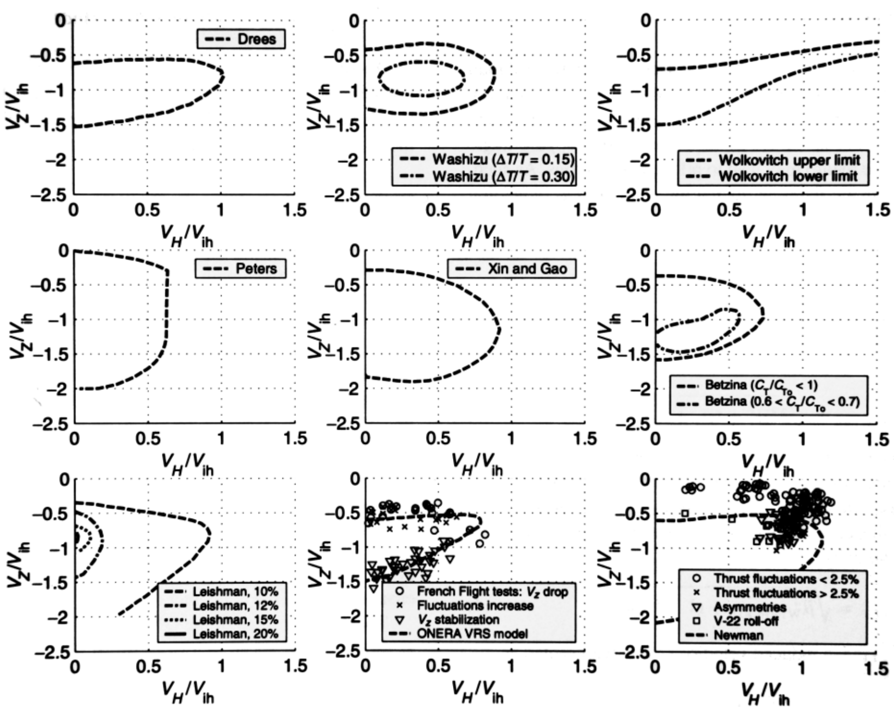

Figure 4 Vortex Ring State boundaries as determined by various studies [7]

To be able to escape the VRS the pilot must have enough collective control to stop the fast rate of descent developing in VRS. Operationally, manoeuvres have been proposed to escape the Vortex Ring State, for example the so-called Vuichard Manoeuvre. It consists of using the pilot lateral cyclic stick to roll and the pedals to give a yaw rotation to move the helicopter sidewards. However, a similar manoeuvre can be performed in a simulation using only longitudinal commands and following the Wolkovitch's boundary conditions of the Vortex Ring State, shown in Figure 5 [3], where it is highlighted how the addition of forward speed can allow the aircraft to remain into the safe region.

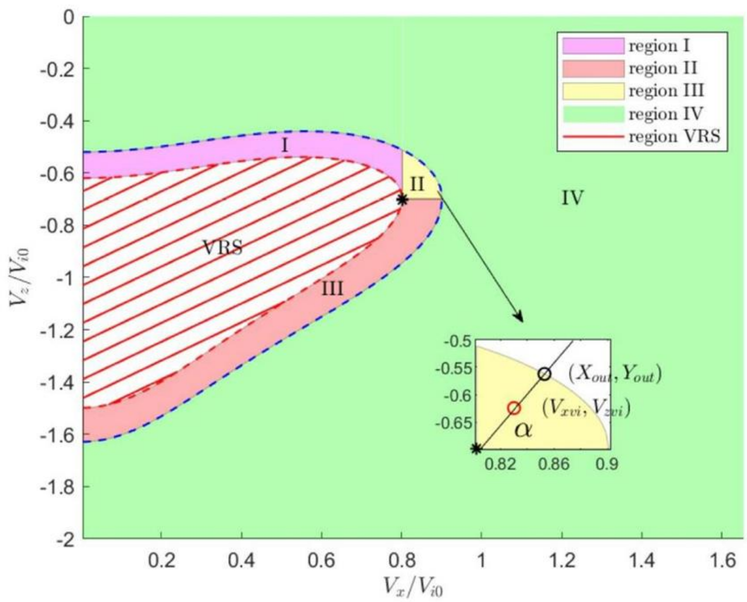

Figure 5: Wolkovitch's boundaries divided into regions [3].

2 Vortex Ring State research at Delft University

To verify the work of Castles and Gray, experiments on a propeller with negative advance ratio were performed in the anechoic wind tunnel of the Low-Speed Laboratory at Delft University of Technology in June 2023. The goal was to understand the consequences of the Vortex Ring formation on the rotor thrust. The experiment conditions of acquisition are summarised in Table *1*. The propeller model used was a two-bladed APC 9"x6" scaled to have a diameter of 30 cm. To obtain the flow velocity around the propeller, the stereoscopic PIV was performed using two double-framed sCMOS with 2560×2160 pixels and 50 mm focal length lenses cameras inclined 25° from each other and a single plane of illumination made by a double pulse Quantel Evergreen EVG00200 Nd:YAG laser with 200 mJ/pulse energy whose thickness was about 1 mm. Results are shown in Figure 6 presenting the transition from the normal descent to Vortex Ring State with the formation of the Vortex ring on the rotor plane. In particular, the pictures show the airflow streamlines for the wind tunnel speeds of 8.5 m/s and 9.5 m/s respectively.

Table 1: Experiment conditions of acquisition.

Measurement	**Values**
Propeller rotative speed [RPM]	4000
Wind tunnel speed (acquisizione spinta) [m/s]	0, 4, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10.5, 11, 11.5, 12, 12.5
Wind tunnel speed (acquisizione PIV) [m/s]	7.5, 8.5, 9.5

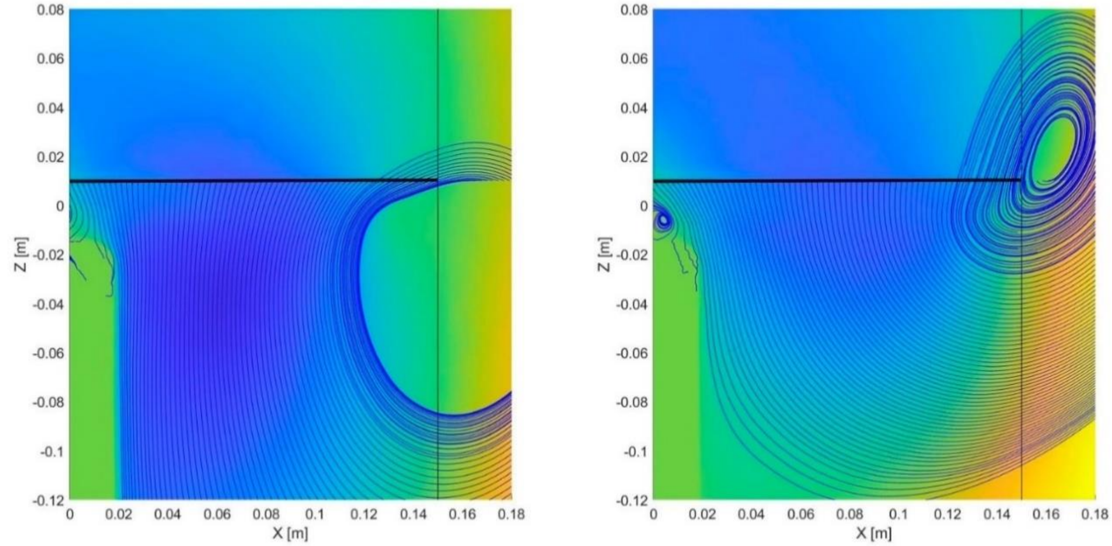

Figure 6: PIV results at Vz 8.5 m/s and 9.5 m/s.

The aerodynamic model used to describe the Vortex Ring State and applied in the descent simulations was built starting from the experimental data taken by Caputo et. Al. [4] in the Low-Speed wind tunnel at the Delft University of Technology using a two-bladed 60”x4” propeller at a fixed rotational speed of 8000 RPM. The results are plotted in Figure 7.

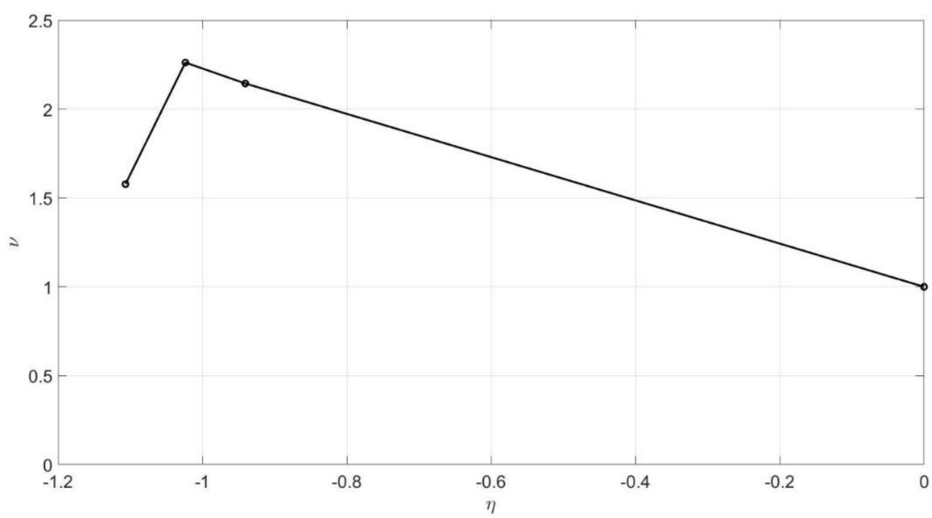

Figure 7: Induced velocity in VRS state [4]

On this set of data, the best fitting using the least square method was performed in order to obtain a non-dimensional curve representative of the trend of the rotor induced velocity in presence of the Vortex Ring. The designated function that best described the experiments was a double exponential, as shown in Equation 3 (terms explained in Equation 4). The constants used to fit the data are a=0.9981, b=-0.8207, c=-2.499e-16 and d=-32.39; the function is divided by a term that contains the non-dimensional forward speed to conform to the phenomenon physics that expects the induced velocity to diminish when the descent becomes oblique (Figure 8).

$$\nu = \frac{a\, e^{b\eta} + c\, e^{d\eta}}{1 + \bar{\mu}^2} \quad (3)$$

$$\nu = \frac{V_i}{V_{ih}} \quad \eta = \frac{V_z}{V_{ih}} \quad \bar{\mu} = \frac{V_x}{V_{ih}} \quad (4)$$

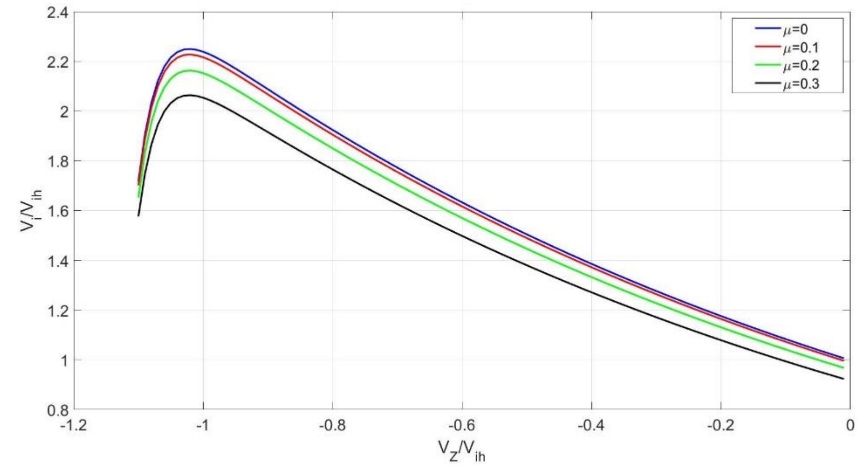

Figure 8: Induced velocity model with Vortex Ring changing the forward speed.

In the experiments performed at Delft University on VRS, Figure 9 shows a drop of thrust when the air speed increases and transitions from slow to moderate. Therefore, in that particular range of descent speed the pilot can find himself in a dangerous situation where applying collective command can be not sufficient to set the helicopter out of the VRS state.

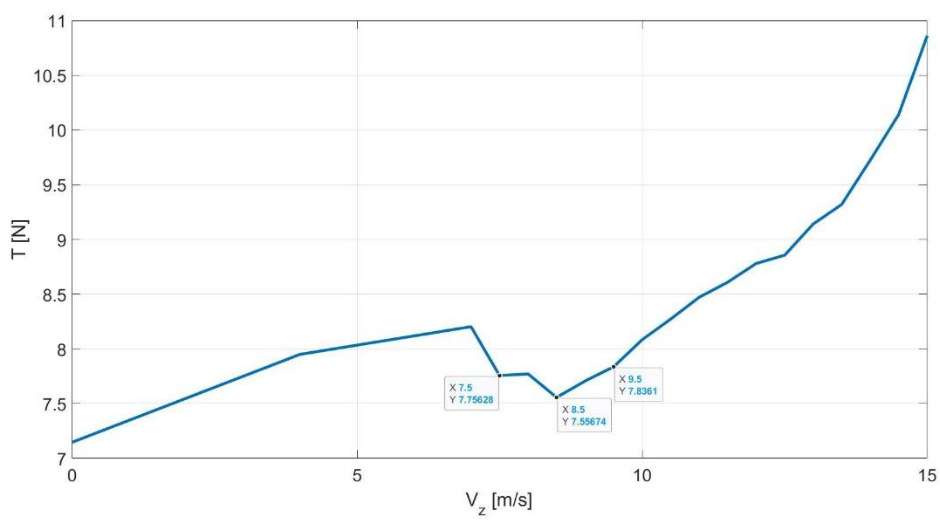

Figure 9: Load cell data that highlight the thrust (N) drop.

To visualise the difference between the presence and the absence of a proper aerodynamic model that captures the phenomenon, the model for a steady-state flow was built starting from the definition of the thrust coefficient by Glauert and the Blade Element Method (Equation 5). The value of induced velocity used for the simulation is the one that makes the difference between the two coefficients equal to zero and it is adimensionalised by the speed at the rotor blades tip.

$$F(\lambda_i) = C_{T,BEM} - G_{T,Glauert} = 0 \tag{5}$$

3 Vortex Ring State Avoidance System for a 3-DOF helicopter

To build an Avoidance System for the Vortex Ring State, Figure *9* was particularly relevant as the aim is to never let the system enter the unsafe region. To be more precise, the value of forward speed adimensionalised by the hover induced velocity should be greater than 0.9 and according to the data used for the simulation this value of V_x is around 6.5 m/s. In order to have a safety margin of 1.5, the desired forward speed is 10 m/s which can be reached with a displacement of the cyclic stick to reach a desired pitch angle θ_f of -5°.
A threshold value of 1.65 of non-dimensional induced velocity, identified performing the descent simulation with Vortex Ring formation, was used to command the activation of the VRS Avoidance System function. The value of non-dimensional induced velocity is evaluated at every step. If the condition of controls loss is not reached, therefore if the induced velocity does not exceed the threshold value, the function is not activated and the cyclic is not displaced. Otherwise, the desired θ_f is set on -5° in the cyclic control law described in Equation 6 where $K_P = K_D = 0.3$.

$$\theta_{1s} = K_P\left(\theta_f - \theta_{f,des}\right) + K_D\, q \tag{6}$$

This function is meant to be activated during hands-off pedals-off flight while upper modes of the Automatic Flight Control System are engaged, such as the altitude and descent rate control. The logic behind it is described in Figure 10 with an application example while the altitude control is active.

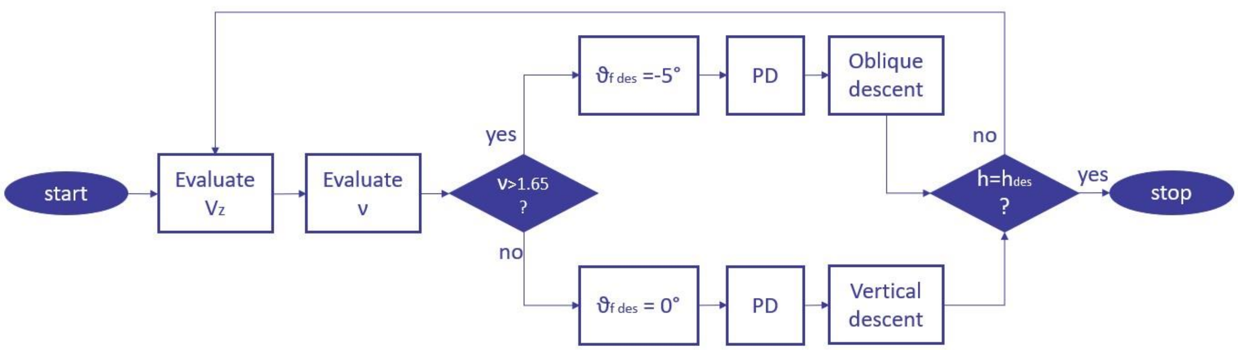

Figure 10: VRS Avoidance System function logic while altitude control is engaged.

4 Simulations results

The starting conditions of the simulations used to verify the Vortex Ring State model and the Avoidance System activation are hover flight with trimmed commands (collective at 5.2125° and cyclic at 0°). After 10 seconds, the collective is set on 2° in order to perform a decent and after other 3 seconds it is restored at trim value. The observation time is 50 seconds. To understand how the Vortex Ring State impacts the pilot commands, the comparison between the steady flow model and the empirical model is necessary and results are shown respectively in Figure 11 and Figure 12.
The steady flow does not impact the command input. The aircraft responds promptly when the collective is reset on the trim angle and stops the descent. This behaviour is typical of what is called a Normal Descent that usually occurs with very low descent rate.

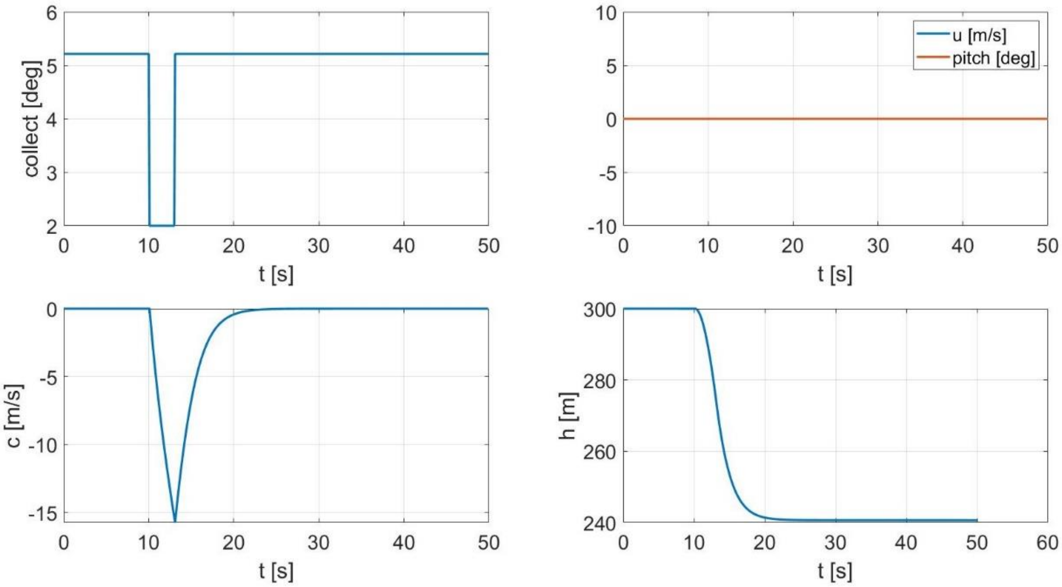

Figure 11: Steady-state flow simulation results.

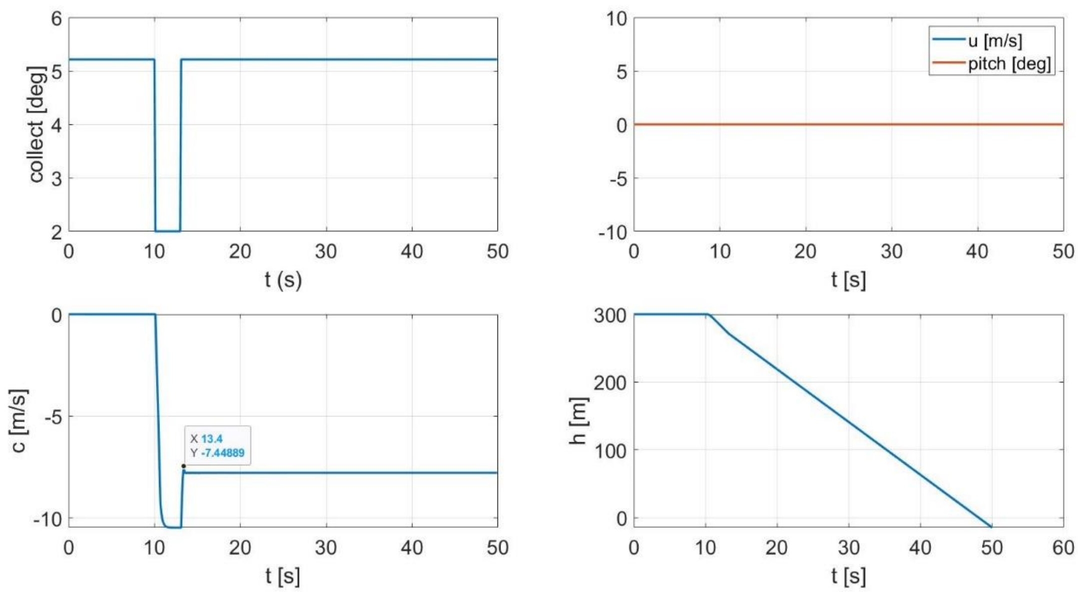

Figure 12: Flow model with Vortex Ring State simulation results.

For the same parameters, initial conditions and input conditions as the previous simulation, with the addition of the Vortex Ring State model the system does not stop the descent when the collective is reset on trim. This means that the helicopter did not respond to the given input and kept on descending with a command loss.
To verify that the Avoidance System works, a simulation with the condition of the induced velocity threshold is performed keeping constant all of the flight conditions and the input command. Results are shown in Figure 13. The induced velocity got to the threshold value and activated the Avoidance System.

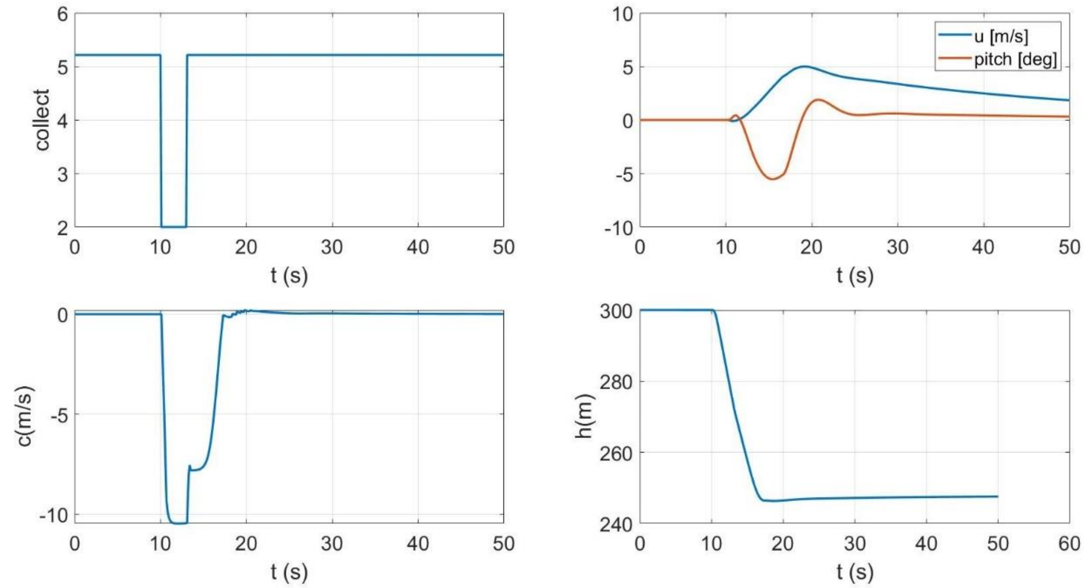

Figure 13: Flow model with Vortex Ring State and Avoidance System simulation results.

The helicopter started getting into the Vortex Ring State but in the meantime the pitch angle is changed according to the desired pitch angle in order to have the forward speed needed to exit of the vortex. When the critical phase is over, the forward speed should be reset and the longitudinal cyclic should be repositioned in equilibrium flight.
To verify that the Avoidance System activates itself only when it is required, the logic shown in Figure 10 is implemented when flying the descending flight. The initial altitude is set at 300 m and the desired final altitude at 250 m.

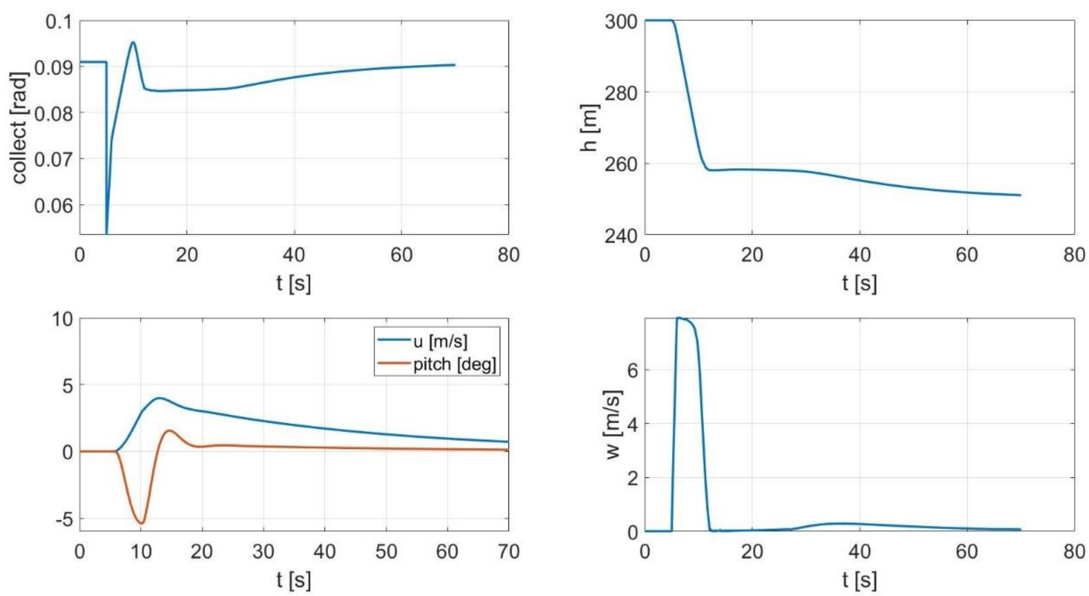

Figure 14: Altitude control upper mode with Avoidance System active.

Since the difference in altitude is considerable but still moderate, the cyclic command was activated but it did not allow the forward speed to reach high values. The helicopter moved forward just enough to elude the phenomenon. This proves also that the Avoidance System can auto-calibrate to ensure that the aircraft gets to the desired altitude safely and not with an exaggerated oblique descent.
It is clear from the previous simulations that the descent rate is crucial to verify the presence of the Vortex Ring State. The VRS Avoidance System function can be implemented also inside the rate of climb control loop and results for a desired ROC of -5 m/s with and without the function are shown in Figure *15* and Figure *16*.

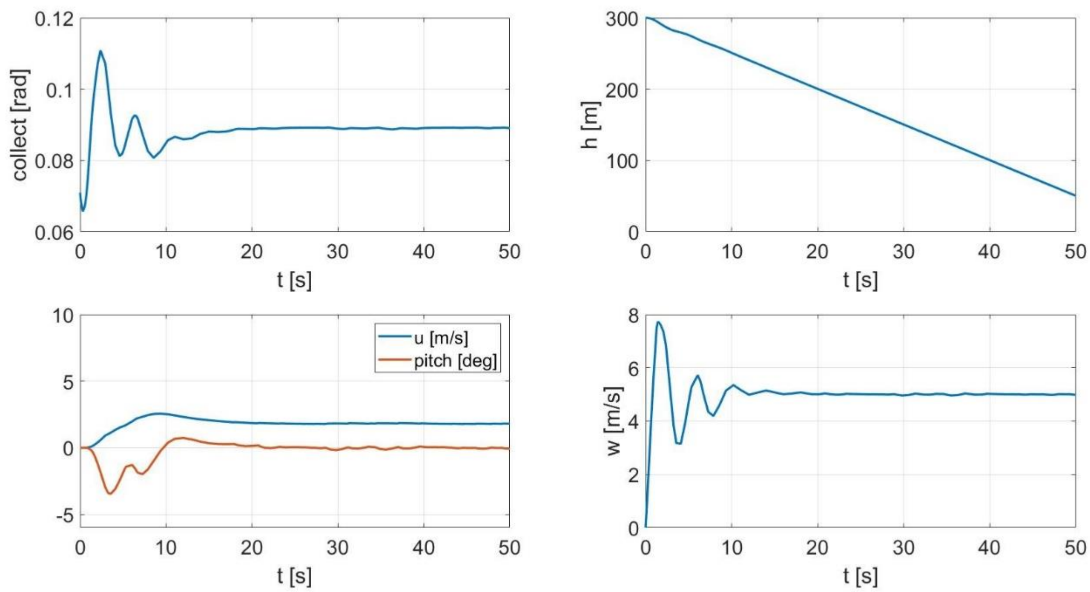

Figure 15: Rate of climb control upper mode with Avoidance System active.

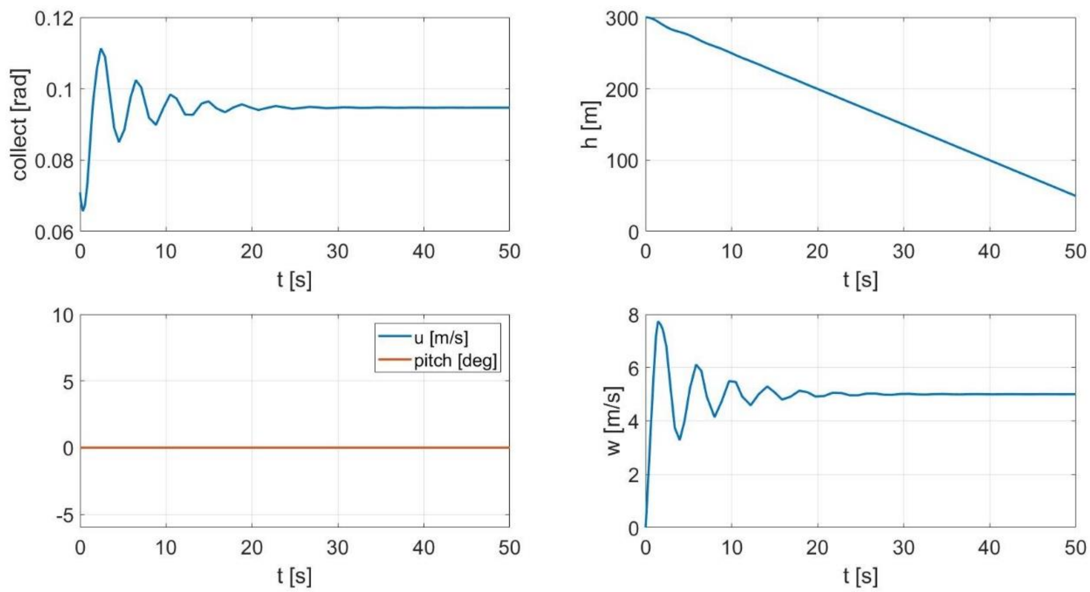

Figure 16: Rate of climb control upper mode without Avoidance System.

Comparing the two images, it is noticeable that the Avoidance System in this situation plays an important role. In its presence and activated when needed allowed the helicopter to have a faster response to the step command. This is highlighted in the collective and downward speed plots where the settling time and the oscillations are diminished by the addition of some forward speed. This means that the activation of the cyclic makes the system more damped than the one without it. This can be useful not only to improve the performance of the aircraft but also to improve the handling qualities as the oscillations are significantly reduced when the Avoidance System is in use.

5 Conclusions

The presence of the vortex ring changes the expected distribution of the induced velocity, that becomes the main tool to build a model of the phenomenon that can be used in simulations in order to predict and observe the behaviour of the VTOL aircraft during the descent. To create the aerodynamic model, data from a previous experiment performed by Caputo et. al. [4] in 2022 at Delft University of Technology were used. A best fitting through the root mean squares technique was applied onto the data in order to get the trend of the induced velocity increment during the Vortex Ring State, the expression of the curve was then divided by a term that allow the model to follow the principle for which the induced velocity should decrease when a forward speed is given to the aircraft. The so-built model was then inserted into the Momentum Theory in order to obtain a general model used to calculate the induced velocity in every flight condition. Another model for the steady-state flow was created in order to see the response of the system to the ideal flow and compare it to the one observed with the Vortex Ring State model in use.
Considering an initial altitude of 300 m and a pulse collective input that moves the lever from the trim condition to 2° and then again onto trim angle, the helicopter had a normal descent with the steady-state flow and a controls loss with the Vortex Ring State model. This developed model allowed to make noticeable the presence of the VRS phenomenon. The Vortex Ring State started getting an impact on the helicopter at 13.4 seconds when the non-dimensional induced velocity had a value of 1.65. If the calculated non-dimensional induced velocity was higher than 1.65, the Avoidance System should have activated with a control law for the collective. The latter is necessary to avoid the dynamic instability given by the use of the collective stick. This control law invlolves the pitch angle and its derivative multiplied by two gains. The Avoidance Systems gives the aircraft a forward speed that should lower the induced velocity value (like it was theorised by Wolkowitch [3] in his Vortex Ring State boundaries studies).
Considering this new addition in the plant and repeating the simulation, the helicopter did not enter into a free fall; instead, the Avoidance System in action prevented the helicopter to lose its controls and the altitude trend results almost the same as the one seen in the simulation with steady-state flow. Imposing the altitude difference, the simulations highlighted that the Avoidance System is capable of activate only when needed, in other words, only when the altitude difference was enough to have a descent rate sufficient to see the Vortex Ring State. Moreover, with the set value of desired pitch value in the cyclic control law, the system manged to calibrate the forward speed to get out of the vortex ring but without exaggerating the oblique descent.
As the descent rate is so important for the detection of the Vortex Ring State, control laws for the collective were built and simulations were performed at the descent rate of -5 m/s. When the vortex ring was at its maximum development, according to the theory of the phenomenon, the activation of the Avoidance System improved the performance of the helicopter.

A further development can be the extension of the helicopter model from three to six degrees of freedom, the static model can be converted into a dynamic model and the Avoidance System can be made using a Model Reference Adaptive Controller (MRAC) introducing an uncertainty in the plant regarding the descent rate.

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