EXIT FROM VORTEX RING STATE – A COMPARATIVE STUDY OF DIFFERENT RECOVERY TECHNIQUES

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Abstract

In this study, different recovery methods for exiting from different phases of vortex ring state are compared with respect to loss of altitude and piloting complexity. The investigation is based on maneuver simulations carried out by a coupled flight mechanics – free-wake-code simulation environment, including an autopilot for a detailed model of the BK117 D-3 in comparison to flight test data. The maneuver simulations comprise the phase of entering the vortex ring state from hover over incipient vortex ring state, up to deep vortex ring state with a high, but constant rate of descent. This is followed by the application and comparison of four different recovery techniques: *Traditional, Power-assisted, Vuichard,* and *Pulling collective only*, each with equivalent input strokes. The methods are compared with respect to effective altitude loss and piloting complexity. Within all successful recovery maneuvers, the *Traditional* method always led to the highest loss of altitude until recovery.

1. INTRODUCTION

The Vortex Ring State (VRS) is a potentially dangerous, usually unintended flight state of a helicopter, leading to descent rates of >3000 ft/min that can occur within a few seconds from normal operation. It should therefore be avoided by any means, or at least recovered as early as possible by adequate flight control inputs to re-obtain a stable, controlled level flight. To allow for a fast recovery with the least altitude loss, it is crucial, that the pilot is fully aware of the best exit strategy and is adequately trained to apply it. Different piloting strategies are known and currently vividly discussed within the community and authorities. A lot of the discussions focus on the effectiveness of the different recovery techniques with respect to loss of altitude and complexity of execution. The comparison of such maneuvers based on flight test is difficult though, as pilots should normally avoid this flight state, which makes it difficult to obtain comprehensive flight test data. Further on, VRS it is a highly dynamic maneuver, with a high level of unsteadiness, which makes it difficult to generate quantitatively comparable results. Simulations like discussed in Ref. 1 and Ref. 2 allow to investigate and compare VRS and its recovery methods quantitatively and in more physical detail to reveal the underlying aerodynamic phenomena. Further on, validated dynamic maneuver simulations based on manufacturer helicopter models can close the gap between real flight tests and generic simulations. Therefore, a physically accurate and validated VRS simulation of a BK117 D-3 was developed to allow for the comparative assessment of the different recovery techniques and to support the further optimization of the piloting strategy. Ultimately, this can increase flight-safety by reducing catastrophic VRS encounters.

2. SIMULATION SETUP

The simulations presented in this paper were created by the use of two coupled simulations tools. The Airbus flight mechanics simulation code GENSIM and the Free-Wake-/Panel-Method code UPM (Unsteady Panel Method) by DLR-AS, described in Ref. 3.

GENSIM provides 6-DoF-trim and time domain simulation capabilities based on 3D-polars for non-rotating bodies and wings. As rotor model, a rigid blade rotor model is used considering flap, lead-lag, blade and control torsion for the rotor blade dynamics and blade-element-momentum-theory combined with different inflow models. Further on, an auto-pilot model is available to stabilize the time domain simulation. As helicopter model, the latest version of the H145, a BK117 D-3 was used for simulation and flight test. The BK117 D-3 is a twin-engine helicopter with a maximum takeoff weight (MTOW) of 3800kg, a Fenestron anti-torque system and a five-bladed bearing-less main rotor system (BMR).

Since the fast, but simple aerodynamic models of GENSIM are not capable of capturing complex 3D-Aerodynamic phenomena like re-circulation in Vortex Ring State, they need to be replaced by unsteady 3D-Aerodynamics. Ideally this could be done by high fidelity unsteady Navier-Stokes based CFD, but the computational requirements for numerous maneuver-simulations in the order of up to a minute flight time are currently excessively too high in an industrial environment. Therefore, the Free-Wake-/ Panel-Method Simulation Tool UPM, developed by DLR-AS, was chosen. UPM allows carrying out unsteady aerodynamic simulations on a single state-of-the-art workstation or one cluster node within single days. However, due to the very strong mutual interactions of the vortex filaments in the vortex ring, the wake-panels are too instable for generating reasonable results. Therefore, instead of wake-panels, wake-particles featured by the plugged in open-source-solver DUST described in Ref. 4 were chosen. In contrast to Navier-Stokes based CFD, flow separation effects are not captured inherently by panel methods, but for the rotor blades a combined lifting line method accounts for stall effects, although they are not considered to be relevant for the results in these VRS simulations.

The UPM-Model of the BK117 D-3 comprises a D-3 model of the non-rotating surfaces with 3700 surface elements and a main rotor with 30 panels in spanwise direction and 25 panels in chordwise direction per blade. For each direction the panel density is increased towards the boundaries (root, tip, leading-/trailing edge) to capture the relevant physics. Based on experience, this rotor panel resolution and distribution provides sufficiently accurate results. The Fenestron currently cannot be modeled in UPM yet, therefore only the internal GENSIM model is used. But since the Fenestron is outside of the vortex ring, as can be seen in Figure 6 of chapter 3.2, there is, apart from a flow re-direction, no direct and strong aerodynamic interaction. Therefore, it is considered that the internal GENSIM Fenestron model works sufficiently accurate.

The two codes are coupled for trim and maneuver simulations on a weak basis. This means that the forces, motions and attitudes as well as the induced velocities between both codes are updated after each full main rotor revolution, according to the scheme in Figure 1. This is considered to be sufficiently accurate for this low frequency-type of maneuver.

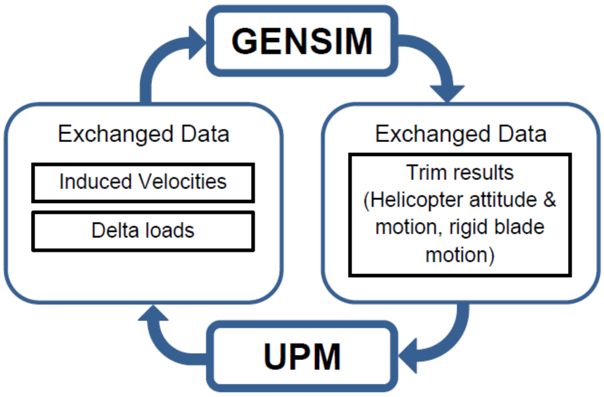


Figure 1: Coupling of UPM and GENSIM based on Ref. 5

3. ENTRY INTO VORTEX RING STATE

In order to investigate the different recovery methods from deep VRS, first a common starting point in deep VRS is required. As this flight state is in reality and also in simulation quite unsteady, it is not possible to reliably find directly a steady trim state in deep VRS in the simulation. Further on, it is of high interest to re-simulate the entry into deep VRS in order to validate the simulation toolchain against flight test. Therefore, one of the flight tests starting condition, a high hover point with a small climb rate was taken as reference for the simulation start.

3.1. Flight conditions and control input

In *Table 1* the boundary conditions are provided which were used to find an initial trimmed flight condition comparable to the performed flight test.

Table 1: Flight conditions at maneuver start

Boundary condition	Value
Altitude	6660ft = 2030m
Outside Air Temperature	4°C
Helicopter Mass	3085kg
Altitude Rate	+1.3m/s (Climb)
Horizontal velocity	0.0m/s

Starting from this steady trim condition, in order to lead the simulation into the VRS condition, the collective was reduced by a total of 1.8° (~11% of total collective range), as it was done during the reference flight test. First by a reduction of 2% within 0.3s, followed 1.5s later by another reduction of 9% within 2s. Apart from attitude hold corrections from the autopilot to keep the helicopter stable, no other inputs were introduced.

3.2. Simulation results and validation vs. flight test data

In Figure 2, the rate of descent (ROD) recorded from the flight test and evaluated from the simulation is shown for the initial part of the maneuver, the transition from Hover with a small climb rate of 1.3m/s to a quasistatic descent rate in deep VRS. After lowering the collective, the rate of descent increases quickly with an acceleration of ~1.2 m/s². In the first six seconds after lowering the collective (Figure *2*, *Time*=8s), the descent rate over time of the helicopter in flight test and simulation is very similar up to a rate of ~6m/s. It should be mentioned that at *Time*=5.5s, there is a slight temporary reduction of the descent rate increase which occurs in the flight test about one second later at *Time*=6.5s. After *Time*=8s the rate of descent starts to increase faster in the simulation up to a descent rate of ~12 m/s within 2s, where the acceleration is stopped and the rate of descent remains constant. In the flight test, the increase of the rate of descent is also observed, but starting about 2s later (Figure 2, *Time*=10s) from a descent rate of ~8 m/s on up to ~16 m/s, from where it also remains constant.

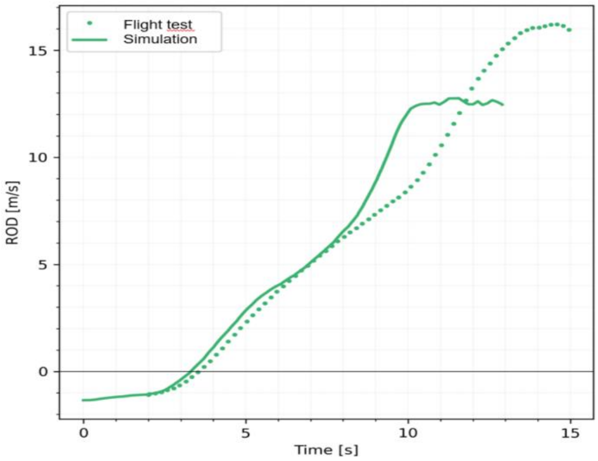


Figure 2: Rate of descent over time for equivalent flight conditions and control inputs in flight test and simulation

Consequently, the basic behavior of both, flight test and simulation, including the gradient change-behavior is equivalent. Just the overall magnitude and consequently also the maximum rate of descent reached is about 20% lower in simulation compared to flight test. Also, the maximum rate of descent is reached about four seconds earlier in the simulation. This is also confirmed by comparing the main rotor thrust over time in Figure 3 and over rate of descent in Figure 4, where the curves also deviate in particular for higher rates of descent, but show comparable trends and absolute thrust values.

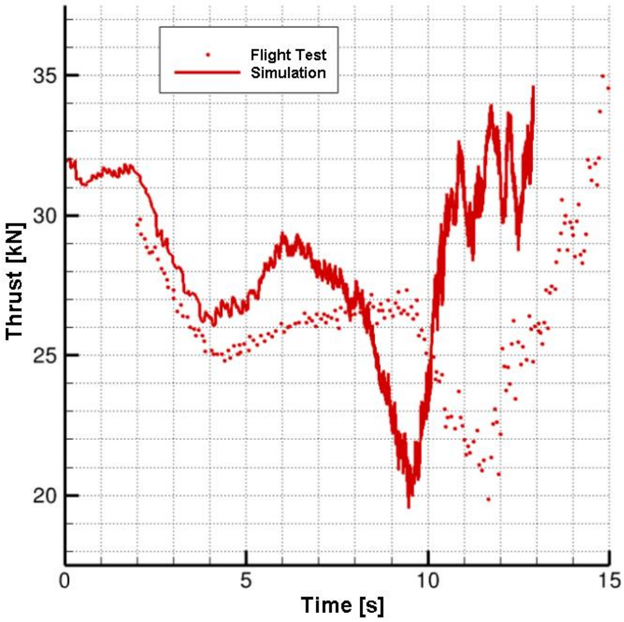


Figure 3: Rotor thrust over time for equivalent control inputs in flight test and simulation

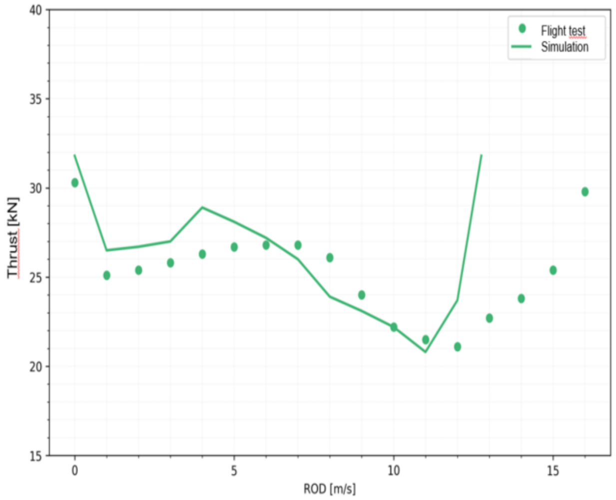


Figure 4: Thrust over rate of descent for equivalent control inputs in flight test and simulation

This confirms that the underlying physics are captured well, nevertheless with a certain scope for improvement for reaching equivalent descent rates. The root cause for this quantitative difference is not identified yet, but possible reasons are the constant vortex core radius limitation and the absence of a vortex aging model in the particle simulation.

In Figure 5 the helicopter is depicted with its according main rotor wake system for hover at the start of the maneuver and in deep VRS in Figure 6.

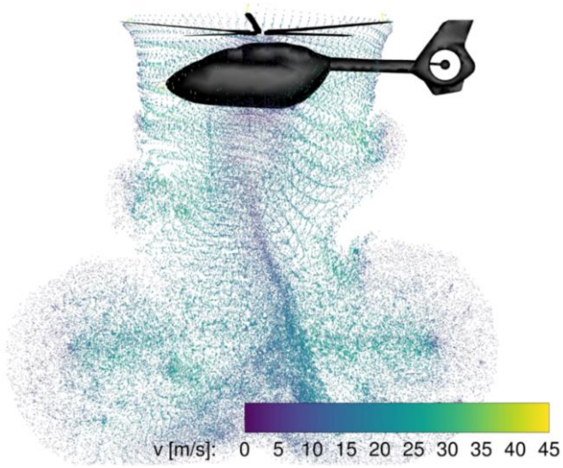


Figure 5: BK117 D-3 - Hover at start of maneuver

In both pictures the wake structure shows the expected behavior. In hover a clear stable downwash without recirculation and in deep VRS the typical donut-shaped vortex re-ingestion ring with its center just above the rotor tip. In addition, in deep VRS very high induced velocities of more than 45m/s in particular at the outer part of the rotor disc are observed. This high velocity seems to be concentrated at the rear part of the rotor, but this changes during the simulation as the vortex ring is dynamically changing its shape and velocity distribution over time. Also, the particles depict very well that in this condition there is only limited exchange between the air in the vortex ring and the surrounding air. This means that the borders of the recirculating bubble depict in the first order an isolated, recirculating air volume which is seen by the external air as a blunt drag body attached to the main rotor blades, stabilizing the helicopter at a sink rate where its drag equals the helicopters gravity force.

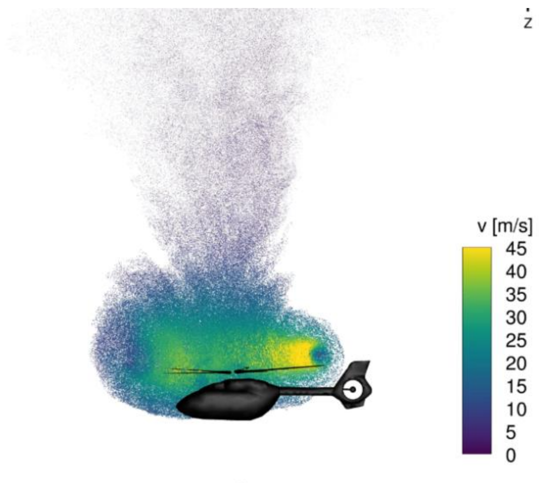


Figure 6: BK117 D-3 in deep VRS at *Time*=11s

A first order estimation for the outer radius of the vortex ring of 8m based on the boundary streamlines in Figure 7 and an assumed drag coefficient of 1.0 yields a lift force of about 60% of the HC mass. The remaining difference may be explained by the remaining air- and by that the momentum-exchange of the vortex ring with the free flow. Even though no detailed quantitative evaluation is available here, this further supports the validity of the simulation from a phenomenological point of view.

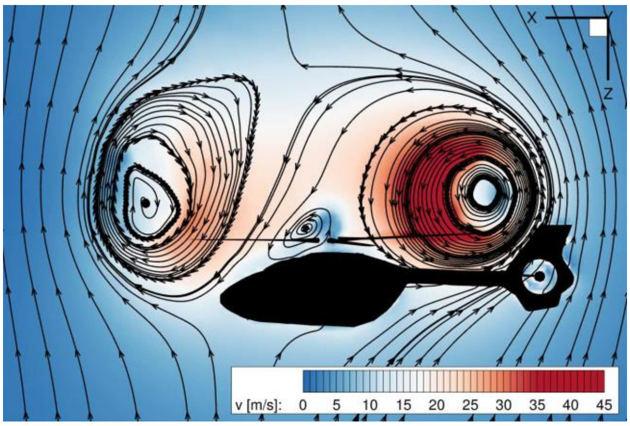


Figure 7: Visualization of streamlines and velocity for a ROD = 12 m/s

4. EXIT FROM DEEP VRS

In order to be comparable, all following recovery maneuver simulations start from the same flight state at the end of the “Entry into VRS” simulation in deep VRS presented in chapter 3. Due to the unsteady nature of the Vortex Ring, its structure is not perfectly line-symmetric with respect to the rotor shaft. This asymmetry can have an influence e.g., on the recovery time and consequently also the loss of altitude until recovery of a maneuver. In order to be perfectly comparable, a series of maneuvers with the same inputs at different start times of the quasi-steady deep VRS condition would be required to assess the impact of the unsteadiness on the results. In the frame of the investigations this influence could not be evaluated yet. However, the conclusions are drawn with this effect in mind, so that for most cases it should not impact the findings. For the cases where this effect matters, it is discussed.

In the following sub-chapters, first the control strategy of each maneuver technique is described, followed by a flight path analysis. For all maneuvers, comparable control inputs with equal magnitudes were applied.

4.1. ***Traditional*** recovery

In the *Traditional* recovery method, first the collective is lowered and a longitudinal forward cyclic input is applied at the same time. Consequently, the helicopter pitches nose down, which leads to a breakdown of the vortex ring at the rotor and the helicopter accelerates forward into clean air, leaving the ring behind. As soon as the vortex ring is gone, the collective is pulled up again to regain thrust and stop the descent. In the simulation as collective input of -1.8deg (-11%) was applied. In the longitudinal forward direction 5° (23%) were applied until the helicopter reaches a nose down pitch angle of 20°, which is then held constant by the autopilot. As soon as 20 knots forward speed are reached, +3.6° (+22%) are applied in the collective, in order to retrieve the same collective setting as in hover before entry into VRS. The maneuver ends with a stabilized level flight of about 22m/s (45kts) In Figure 8, the exit from VRS by applying the *Traditional* recovery method is depicted in four steps. It can be seen that the method successfully stops the descent. However, from recovery start to level flight 77m (252ft) of altitude are lost in the simulations, which can be considered as a large height loss. The reason is, that by lowering the collective at the beginning of the maneuver, at the time when the helicopter has left VRS, the rotor does not provide sufficient thrust to decelerate the descent and recover a level flight. The transition to level flight is not started before the decision of the pilot to pull the collective when he is of the opinion that he has left the VRS, which may vary significantly between pilots and the reactivity of the airspeed indicator.

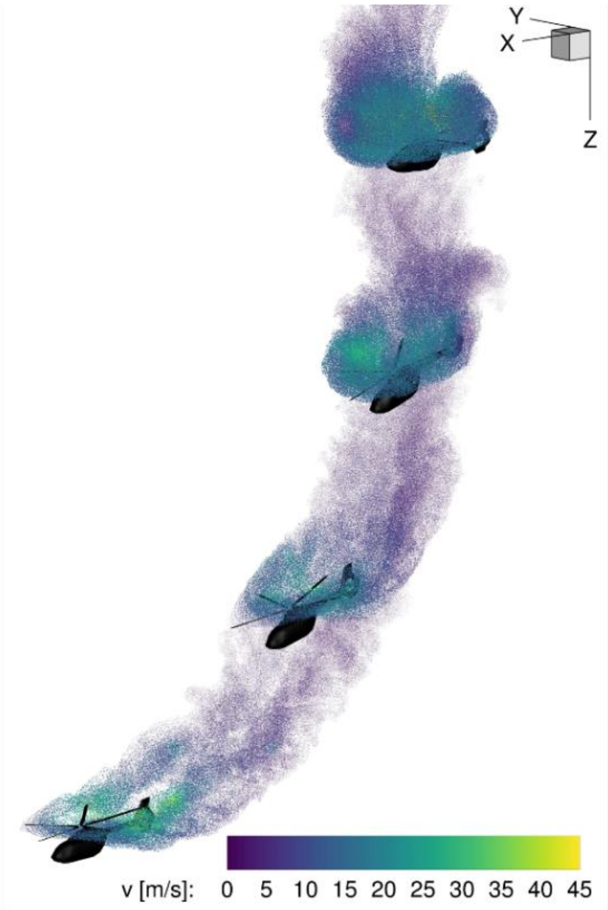


Figure 8: Flight path of traditional recovery method on a BK117 D-3

The question behind this recovery technique is, why it is recommended to lower the collective at the beginning of the maneuver. The typical rational is the intention to end an assumed stall condition of the rotor blades and to bring the rotor blades back to normal operation. However as depicted in Figure 6, the induced velocity in VRS is significantly increased in particular in the outer region of the rotor compared to the normal flight condition shown in Figure 5. Consequently, the incidence angle on the blades is reduced, which excludes a stall phenomenon and further explains the thrust reduction of the rotor in this condition at the same time.

Another reason may be the risk of a potential rpm drop due to increased rotor loading and reaching the engines power limit while exiting the VRS. However, this can be easily handled by the pilot as required during the maneuver. The highest priority of the pilot should remain avoiding contact with the ground, for which avoiding high rates of descent by high rotor thrust is key.

Also, a potentially higher load factor when exiting from VRS with pulled high collective could be a problem for the structural loads of the rotor system. However, no critical loads have been reported by the crew for any of the VRS flight tests with the BMR-System of BK117 D-3. Also, neither the flight test data, nor the simulation show relevant differences of the load factor compared to the other recovery techniques.

Consequently, no reason can be identified why lowering the collective at the beginning of the VRS recovery maneuver is beneficial.

4.2. ***Power-assisted*** **recovery (*Airbus method*)**

This recovery method proposed by Airbus follows almost the same control strategy as the *Traditional* method, but with the crucial difference, that the collective is not lowered, but increased immediately at the beginning of the recovery maneuver simultaneously with the longitudinal forward cyclic input. In the simulation the collective was increased by +1.8° (+11%) and again 5° (23%) were applied in longitudinal forward direction. This leads to an immediate thrust increase as soon as the vortex ring is broken by the nose-down pitch change and consequent horizontal acceleration of the helicopter, ending with a stabilized forward level flight of about 25m/s (49kts). By doing so, the descent is stopped much faster than with the *Traditional* recovery method and the altitude loss is significantly reduced to 54m (177ft). As for the *Traditional* maneuver, it can be seen in Figure 9, that at the end of the maneuver the helicopter reaches a stable forward level flight, where the risk of re-entering the VRS is extremely low.

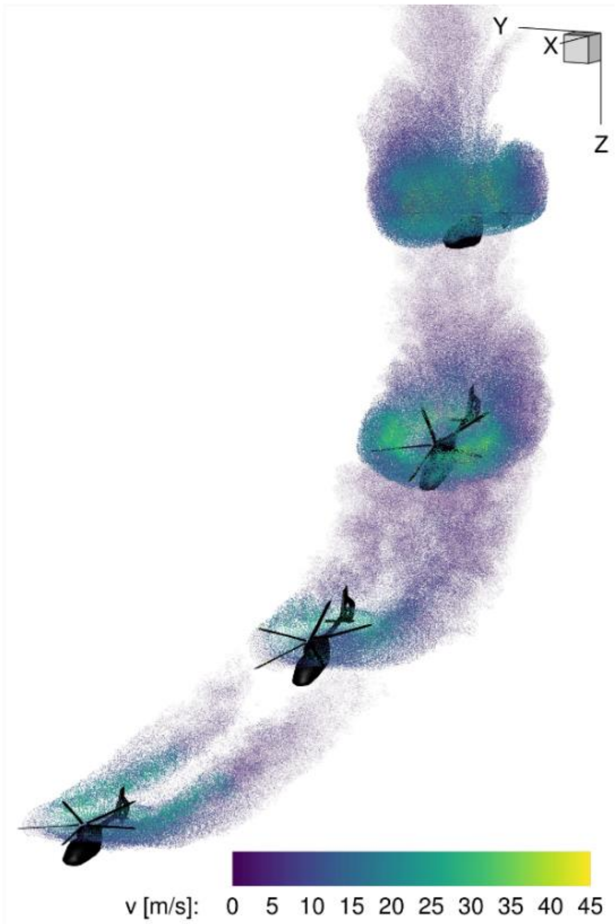


Figure 9: Flight path of the *Power-assisted* recovery method on a BK117 D-3

4.3. *Vuichard* recovery

For the so-called *Vuichard* recovery method it is relevant to know the rotational direction of the rotor as it determines, to which side the maneuver has to be performed. For counter clockwise (CCW) turning rotors, like the BK117 D-3, the maneuver is performed to the right. The maneuver starts with three control inputs at the same time. Like in the *Power-assisted* recovery, the collective is pulled by 1.8° (+11%) in order to increase the thrust as soon as the VRS breaks down. At the same time, 5° (35%) right lateral cyclic is applied to roll to the right and in addition left pedal is applied to increase the thrust at the tail rotor to the right and to counteract the additional torque of the main rotor. During this maneuver, the simulation shows that the vortex ring is broken by the lateral roll and initial acceleration to the right. The idea behind is, that due to the lower moment of inertia in roll and by the additional sideward thrust of the tail rotor, the helicopter is able to roll and accelerate faster compared to the longitudinal recovery techniques. Consequently, the vortex ring is broken faster, which leads to less loss of altitude. In the simulation the maneuver, depicted in Figure 10, leads to a fast recovery with just 37m (121ft) loss of altitude.

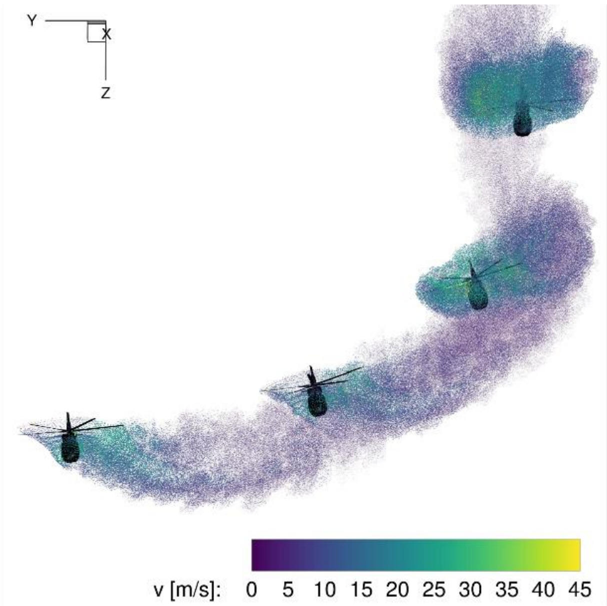


Figure 10: Flight path of *Vuichard* recovery method on a BK117 D-3

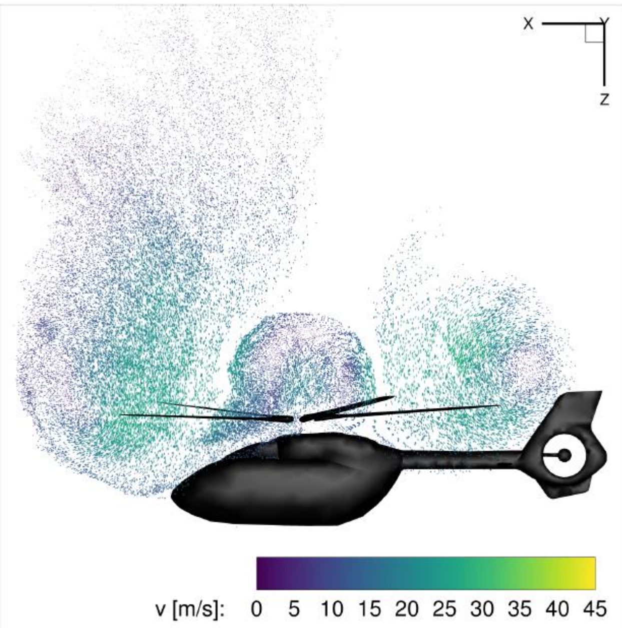
The reason for pulling the collective is the same like in the *Power-assisted* recovery method, to generate thrust directly after breaking the vortex ring. For clockwise rotating rotors the same actions have to be performed towards the left side, requiring inverse cyclic and pedal inputs compared to CCW rotors. It is not excluded that the recovery method also works to the "wrong" side, but it might be limited by the negative thrust capabilities of the tail rotor..

At the end of the *Vuichard* recovery, the aircraft regains a hover flight condition. This is different from the *Traditional* and *Power-assisted* recovery methods, which end in stabilized level forward flight.

4.4. *Pulling collective only* recovery

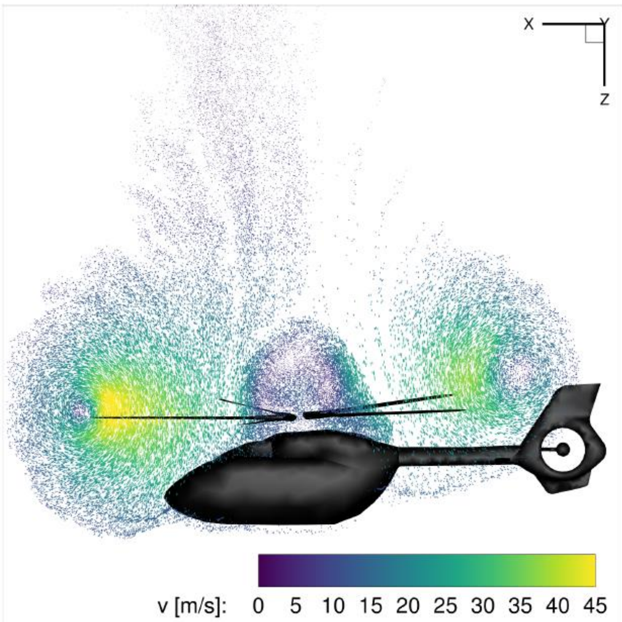
The most intuitive reaction of a pilot facing an increasing descent rate is to pull the collective lever. However, in deep VRS, this strategy is known to be ineffective, which was also confirmed by the flight tests on the BK117 D-3. Also, in the simulation an increase of the collective by +1.8° (+11%) did not permanently reduce the rate of descent or lead to an exit from VRS. This further proves the validity of the simulation model, and confirms that *Pulling collective only* is not sufficient to recover from a deep VRS without a cyclic input.

The two snapshots in Figure 11 and Figure 12 depict the transient behavior on the rotor after *Pulling collective only*. After the collective input impulse, the rate of descent was lowered in the simulation for a short moment. This can be explained by the disturbed vortex ring in Figure 11. The induced velocities are significantly lower compared to the initial deep VRS condition depicted in Figure 6. However, this effect is not permanent. Just 1.4s later, the vortex ring is re-established again with high induced velocities and an almost equally high rate of descent, as depicted in Figure 12.



(a) Flow pattern at t = 12.5 s

Figure 11: Transient flow pattern after *Pulling collective only* from deep VRS for temporary reduced rate of descent



(b) Flow pattern at t = 13.9 s

Figure 12: Transient flow pattern after *Pulling collective only* from deep VRS after re-stabilization to deep VRS-rate of descent

4.5. Comparison of the recovery strategies from deep VRS

4.5.1. Flight test compared to simulations

In Table 2 the altitude losses are listed for the different recovery techniques from the start of the recovery in deep VRS until level flight condition or hover is reached. The absolute values between flight test and simulation differ, but this can be explained by the different initial descent rates in deep VRS between flight test and simulation.

Table 2: Altitude losses of different recovery techniques from deep VRS

	Pull coll.	Trad.	Power-assisted	Vuichard
Flight	∞	136m	94m	70m
Sim.	∞	77m	54m	36m
Ratio	∞	1.77	1.74	1.94

However, the relative losses of the simulations are fully consistent with the flight test results as can be seen from the ratios between the recovery altitudes obtained in flight versus the theoretical simulation results as listed in Table 2. Also, the kinetic descent energy ratio between flight test and simulation of 1.78 (Eq.1) is similar to the recovery altitude ratios which further indicates that the results are consistent with each other.

$$\frac{v_{Descent-FT}^2}{v_{Descent-Sim}^2} = \frac{16m/s^2}{12m/s^2} = 1.78 \quad (1)$$

Potential explanations for the higher ratio of the *Vuichard* recovery are on the one hand differences between the control inputs in the flight tests compared to the simulation, where for the latter the controls were strictly applied with equivalent control inputs compared to the other recovery simulations. On the other hand, there is also the potential impact of the vortex ring unsteadiness described at the beginning of this chapter, valid for flight test and simulation.

4.5.2. Comparison of the recovery methods

In Figure 13 the rates of descent of the different maneuvers are depicted over time. The most significant difference between the different rate of descent evolutions is the long plateau at almost full deep VRS rate up to *Time*=15s for the *Traditional* recovery. It takes about 3.5s after the first pilot control input, before the rate of descent starts to decrease. All the other recovery methods for which the collective is increased, start to decrease the ROD almost instantaneously (as does the ultimately ineffective *Pulling collective only*). The *Traditional* recovery and the *Power-assisted* recovery suffer in the first second from a short delay before the rate of descent shows a first change. This may be caused by unfavorable unsteady induced velocity peaks of the vortex ring, delaying the reaction on the commanded cyclic input. The *Power-assisted* recovery is at the beginning almost as effective as the *Vuichard* recovery, but recovers slower in the second half of the maneuver. The reasons for that are not yet analyzed, but an improved control strategy with earlier reduction of the pitch attitude may reduce the loss of altitude further.

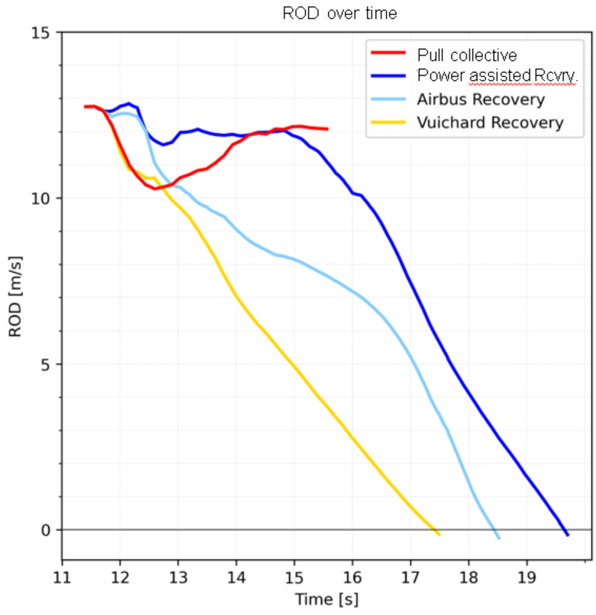


Figure 13: Rate of descent over time for the different recovery techniques in deep VRS

5. EXIT FROM INCIPIENT VRS

In reality the scenario where the aircraft has to recover from deep-VRS is quite rare. Much more often the pilot recognizes the early signs of VRS, like the vertical acceleration or the unsteady behavior in incipient VRS. In order to investigate the effectiveness of the different recovery-techniques in this early phase of VRS, the same recovery maneuvers with the same control inputs like in deep-VRS were applied to the same entry into VRS simulation like in chapter 4. However, in this case, the recoveries were started already at a descent rate of about 5m/s (980ft/min).

In Figure 14 the rates of descent are depicted for all recovery maneuvers starting from the incipient VRS condition. Even much clearer than for the recoveries from deep-VRS, the *Traditional* recovery technique needs by far the most time to recover to a level flight. All other techniques, even *Pulling collective only* are able to instantaneously reduce the rate of descent with almost equal losses of altitude in the range of 13m-15m, listed in *Table 3*.

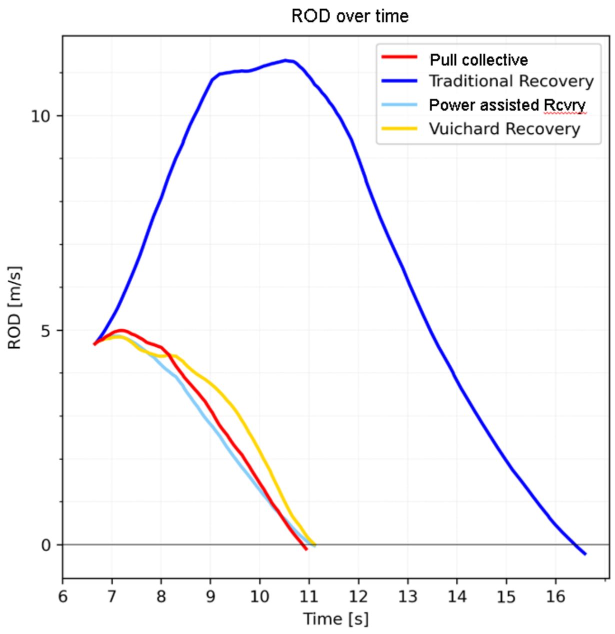


Figure 14: Rate of descent over time for the different recovery techniques in incipient VRS

The altitude loss of the *Traditional* recovery technique with 67m (220ft) is almost as high as in deep VRS and more than four times higher compared to the variants which pull the collective instead of lowering it. As depicted in Figure 14, by lowering the collective at the beginning of the maneuver, the helicopter is forced into descent rates of up to more than 11m/s (2150ft/min), similar to a fully developed VRS, before the recovery starts. Consequently, in agreement with the findings of chapter 4, for incipient VRS the application of recovery methods which pull the collective instead of lowering it, results in significantly lower losses of altitude.

Table 3: Altitude losses of different recovery techniques from incipient VRS

	Pull coll.	Trad.	Power-assisted	Vuichard
Sim.	13m	67m	13m	15m

6. RECOVERIES WITH REDUCED INPUTS

In order to assess the influence of the piloting decisiveness on the effectiveness of the recovery, the simulations of chapter 4 and 5 have been repeated with only 50% of the control input. In Table 4 the altitude losses are provided for the different maneuvers.

Table 4: Altitude losses of different recovery techniques for 50% control input

	Pull coll.	Trad.	Power-assisted	Vuichard
Deep VRS	-	83m	57m	74m
Incip. VRS	34m	69m	38m	29m

Compared to the maneuvers with nominal input, the loss of altitude is always increased. For deep VRS the increase of three to six meters is low, but for the incipient VRS, the altitude losses partly triple by reduced inputs. Another exception is the *Vuichard* recovery maneuver in deep VRS, where the loss of altitude is more than doubled. As it is unlikely that the influence of the piloting input is so much different for the *Vuichard* recovery compared to the *Traditional* or the *Power-assisted* recovery maneuver, the simulation was analyzed in more detail to identify the root cause. It turned out that the reduced lateral cyclic input was not able to initiate the required increase of bank angle instantaneously. As depicted in Figure 15, the bank angle starts to increase from *Time*=11.5s onwards, where the lateral cyclic input was applied, but stops increasing at *Time*=13s. It is then even almost reduced again to its starting value at *Time*=14s by an unsteadiness in the flow field, which delays the exit maneuver. From *Time*=14s on, so 2.5s after the control input, the bank angle finally increases to the intended value. This delay however adds up to an additional loss of altitude of estimated $2.5\text{s} * 12\text{m/s} = 30\text{m}\ (98ft)$. Thus, the unsteadiness of the vortex ring can have a non-negligible impact on the effectiveness of the recovery maneuver, in particular for smaller control inputs where the force and moment changes are in the same order of magnitude to the changes caused by the unsteadiness of the VRS. Further on, reduced inputs always lead to increased losses of altitude until recovery. Therefore, pilots in VRS conditions should always act decisively on the controls, applying an aggressive but not damaging control input to exit as fast as possible.

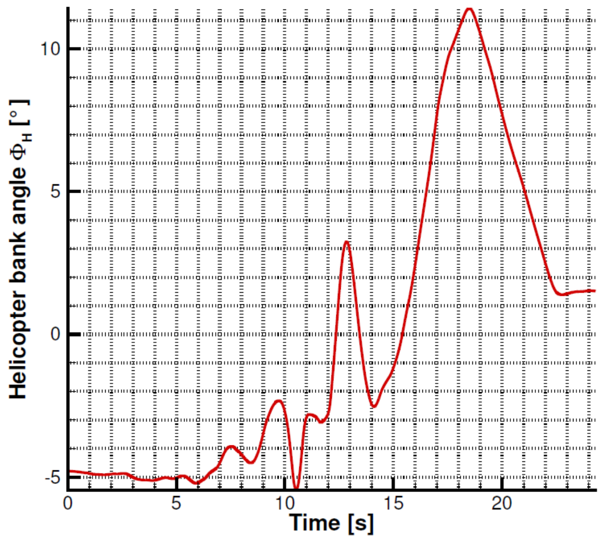


Figure 15: Bank angle over time of the *Vuichard* Maneuver in deep VRS for reduced control input

7. Overall comparison of the recovery strategies

Based on the individual comparisons of the altitude losses between the different recovery strategies, it becomes evident that, if the recovery method is effective, the by far lowest losses of altitudes are obtained by recovery techniques where the collective is pulled simultaneously with cyclic/pedal inputs. The *Traditional* technique, even though it is working, leads in every case to significantly higher losses of altitude. The root cause for this is that lowering the collective always reduces the rotor thrust and increases the descent rate, whilst not contributing to break the vortex ring faster. All other successful techniques build up thrust much faster and consequently lead to a significantly lower loss of altitude.

The *Vuichard* recovery method leads to the lowest loss of altitude from deep VRS with nominal control inputs, and to a similar loss from incipient VRS as the *Power-assisted* recovery or *Pulling collective only*. However, the *Vuichard* method is more complex and requires awareness of the rotational direction of the main rotor and a higher piloting effort in the pedals to maintain the desired attitude. In addition, the maneuver ends in another hover state, which is more prone to re-entering a VRS, whilst the *Traditional* and the *Power-assisted* recovery end in a stable forward level flight condition, where a re-entry into VRS is very unlikely.

8. CONCLUSIONS

1. Lowering the collective in VRS-Recovery maneuvers as defined in the *Traditional* recovery method leads to, partly significantly, higher losses of altitude for all investigated cases. This is most significant in incipient VRS.
2. *Power-assisted* and *Vuichard* recovery are overall the most effective ones.
3. *Vuichard* recovery is very effective with respect to altitude losses, but piloting is complex and it finalizes in another VRS prone hover condition.
4. Piloting in VRS should be very decisive but not damaging in order to minimize altitude loss
5. In incipient vortex ring state, *Pulling collective only* still works, but in deep VRS it is not effective any more
6. The right choice of VRS recovery method, a fast reaction and decisive piloting can reduce the altitude loss in VRS up to ~80%.
7. The results of the simulation toolchain UPM-Gensim compare qualitatively excellent with flight test results. All physical effects are captured and findings are throughout consistent to flight test. Quantitatively, there are still offsets, in particular in the descent rate.

An overall comparison of the described recovery methods led Airbus to the following recommendation: The *Power-assisted* recovery is the preferred method for VRS recovery. In more operational detail, this proposed recovery method mandates to increase collective pitch if residual power is available, or maintain collective pitch is no residual power is available, and translate out of the VRS by applying forward cyclic. In no case the collective pitch shall be decreased. For the most frequent case of a recovery, which is during the incipient stage when the pilot recognizes the imminence of a VRS by the flight physical cues, this method results in the least loss of altitude. If the recovery is performed out of the full VRS, it only results in a slightly higher loss of altitude than the *Vuichard* recovery method. As for the complexity of the maneuver and the required pilot skills, it is the method requiring by far the least pilot skills and is intuitive. It is also not dependent on the direction of rotation of the main rotor, thus eliminating the need for decision making by the pilot in this critical flight state. This is described in the Airbus Helicopters Safety Information Notice 3123-S-00, Ref. 6.

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