EVALUATION OF THE REPRESENTATIVENESS OF FLIGHT MECHANICS MODELS DURING VORTEX-RING-STATE ENTRIES AND RECOVERY MANOEUVRES

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Abstract

Vortex-Ring-State (VRS) remains a dangerous regime leading to several accidents every year. Many studies have been conducted on the phenomenon, but the representativeness of flight mechanics models for prediction of the vortex ring boundaries, and their capability to reproduce the helicopter behaviour during VRS and recovery manoeuvres is still questionable. Therefore, developing fast numerical models able to reproduce this specific aerodynamic rotor regime and validating their representativeness compared to flight tests is an important task to train pilots to VRS in real-time simulator. The "VRS-Helicopter Vortex Ring State Experimental Research", led by EASA and bounded by a contract signed between the EASA and ONERA/DGA-EV, aims to enhance understanding of VRS across two helicopters types, exploring analytical, simulation, and flight test methods. Additionally, it assesses the different recovery manoeuvres. As part of the objectives of this project, the main subject of the paper is to evaluate the correctness of flight mechanics code, VRS models and the reproducibility of recovery techniques. Off-line simulations are compared against flight test data, gathered from the eight flights performed during this project. Additionally, simulator trials were realized in the ONERA research simulator in order to evaluate the representativeness of two different VRS models through piloted simulations. The objective is to highlight the potential shortcomings of the VRS models and thus the reservations to be taken into account when the vortex phenomenon and associated recovery techniques are evaluated through simulations.

1. NOTATION

List of abbreviation

ATR	Artificial Thrust Reduction (VRS model type)
ATT	Attitude Hold mode
DGA-EV	French Flight Test Centre
EASA	European union Aviation Safety Agency
EPNER	École du Personnel Navigant d'Essais et de Réception / the French test pilot school
HOST	Helicopter Overall Simulation Tool
ONERA	Office National d'Études et de Recherche Aérospatiales / French Aerospace Lab.
TRC	Translational Rate Command
VRS	Vortex-Ring-State

List of symbols

Alt	Altitude (ft)
DT0, Coll.	Collective pitch (%)
NG	Gas Generator
PHI	Roll Angle (deg)
PSI	Heading (deg)
RoD	Rate of descent (ft/min)
TETA	Pitch Angle (deg)
TQMOT	Engine Torque (%)
Vh	Horizontal speed (knots)
Vx	Longitudinal speed (knots)
Vy	Lateral speed (knots)
Vz	Vertical speed (ft/min)

2. INTRODUCTION

Vortex-Ring-State (VRS) remains a dangerous regime leading to several accidents every year. Generally, training simulators (and thus flight mechanics codes) are tuned to provide, or to emulate, the main symptoms of the VRS in order to instruct the pilots to this particular flight condition that they should never experience in real flight. While different on each helicopter types, the major symptoms consist in the increase, or at least a change in the vibrations felt on-board and the rapid increase of the descent rate. But the capability of the flight mechanics codes to well represent the helicopter behaviour once in a fully developed VRS or when the pilot is applying a recovery technique is arguable. Therefore, developing numerical models able to reproduce this specific aerodynamic rotor regime and validating their representativeness compared to flight tests is an important task to train pilots to VRS in real-time simulator.

The EASA project “VRS (Helicopter Vortex Ring State Experimental Research)”, launched in November 2022, aims to enhance understanding of VRS across various helicopters types, exploring analytical, simulation, and flight test methods. Additionally, it assesses alternative recovery manoeuvre like the one proposed by Capt. Vuichard. Funded by the European Union's Horizon Europe research and innovation program, this project is bound by a contract signed between the EASA and ONERA/DGA-EV (French flight test centre), for which ONERA was awarded following a public tender process. ONERA and DGA-EV have accomplished together over the past 24 years a large amount of common work aiming at understanding the vortex phenomenon and building up perspectives to contribute to flight safety through numerous flight test campaigns.

The outcome of this research project is twofold. On the one hand, it will provide a better understanding of the VRS phenomenon on different helicopters, the analytical and simulation prediction methods, and flight test methods for its determination. On the other hand, it will provide an indication of the effectiveness of recovery manoeuvres.

As part of the objectives of this project, the main subject of the paper consists in evaluating the correctness of flight mechanics code, different types of VRS models and the reproducibility of recovery techniques. Thus, the first work detailed in the paper consisted in the realization of comparisons between flight test data, gathered during the eight test flight performed during the project, and the flight mechanics code outputs. VRS entries in different flight cases, such as “stabilised” or entries in decelerated flight, in fully developed or at VRS premises, will be analysed. In addition, the response of the simulation model when performing the two types of recovery manoeuvres (the “classical” and the so called Vuichard technique) is analysed.

In order to perform these comparisons, an off line tool was used to follow given flight parameters such as the helicopter airspeeds of attitudes. This tool was also used to perform VRS simulations in other flight conditions than realized in flight tests, enabling the realization of parametric studies.

In addition, simulator trials have been organized to assess the representativeness of the model for both VRS entries and recoveries. One of the pilot who participated to the experimental flight tests reproduced VRS entries and recoveries in the ONERA’s simulator and gave his feedback on the representativeness of the simulation model.

The Federal Aviation Administration launched a similar project on VRS in 2002 and simulator trial results are detailed in [1, 2]. The main objective was to assess the different recovery techniques through different scenarios. The representativeness of the VRS model was not investigated but this question was clearly identified and some flight tests are planned in the future.

Thus, it is hoped that this paper will lay emphasis on some the flight mechanics code limits and lacks of the evaluated VRS models. Dedicated improvements as well as suggestions for future researches will be proposed. Recommendations will be finally issued on the use of simulation models to study the vortex phenomenon and, more importantly, to evaluate the recovery techniques.

It has to be noted that, contrary to [1, 2], the purpose of the present study was not to evaluate the different recovery techniques through the use of simulation, but to assess the capability of real-time VRS models to match with main flight parameters and VRS symptoms and effects.

3. TECHNICAL APPROACH

Many papers have already been published on the VRS phenomenon, including the development of adapted induced speed models in steep descents [3, 4], the analysis of flight tests [5], the development and evaluation of numerical methods for the analysis of rotor wake in VRS conditions [6, 7] or the development of VRS domain criteria [8, 9].

In [10], simulations of the classical and the Vuichard manoeuvres were performed using a more complex method, coupling several methods of Computational Fluid Dynamics with flight dynamics but results of these simulations were not compared to flight data and these types of computations.

In this study, we focussed on fast VRS models enabling real-time simulations and shortly presented hereafter:

- The first one was developed by ONERA and consists in an induced velocity model based on an adaptation of the momentum theory in steep descent. It will be called “OA VRS model” in the paper.
- The second one is representative of VRS models used in training simulators, and consists in an artificial rotor thrust reduction

occurring when the helicopter model enters a predefined VRS domain in terms of forward and vertical speeds seen in rotor frame. It will be called “ATR VRS model” later in the paper.

It was not planned to use more complex methods such as rotor free wake models or even less CFD computations. Free wake models are certainly a good way to reproduce VRS conditions as computing a more realistic rotor wake. Nevertheless, performing a strong coupling between flight mechanics and rotor wake model remains a challenging task especially to reproduce VRS flight cases for which it is mandatory to control, or at least, to stabilize the helicopter model. In addition, performing real-time simulations with these models is still impossible.

Two helicopter models were tested, a Fennec AS-550 and a Dauphin AS365N, corresponding to the machines operated by DGA-EV. Off-line simulation comparisons were mainly done with the Fennec model while simulator trials involved both helicopter types.

3.1. ONERA VRS model description

Simulations have been performed with the Airbus Helicopters flight mechanics code HOST, integrating a specific induced velocity model developed by ONERA in the 2000s and detailed in [1, 2]. As shown in Fig. 1, this model mainly consists in linking the branches of the momentum theory between climb and very high descent rates, corresponding to the wind-mill brake state. This model was tuned to match to available induced velocity measures from publications and from a dedicated flight test campaign performed by ONERA and DGA-EV in the 2000s.

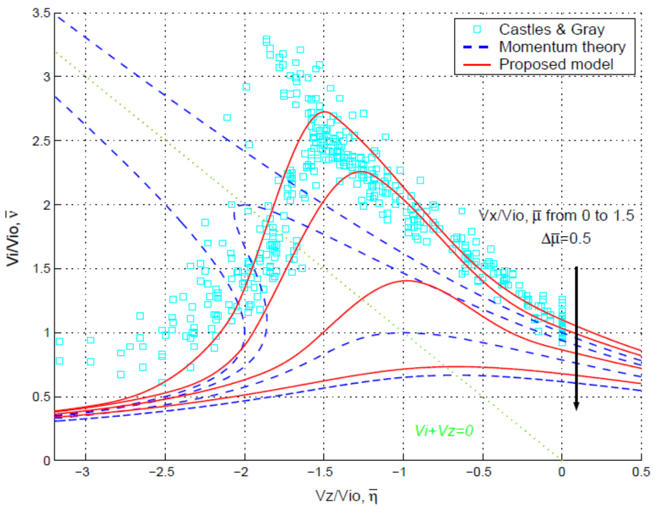

Fig. 1. ONERA induced velocity model in steep descent

Previous papers [3, 4] presented comparisons between the OA VRS model and Dauphin flight test data as shown in Fig. 2. In this example, successive collective (DT0) decreases were performed while maintaining the horizontal speed (Vh). At around 85 s, a slight collective decrease generates the characteristic drop of vertical speed (Vz). Absolute vertical speed values in simulation and in flight are a bit different, but the drop is well captured by the model, leading to a similar maximum value of –15 m/s (-2950 ft/min). As this will be discussed later, most of the comparisons were performed in “stabilised and smooth” VRS entries, i.e. slight successive collective decrease, at constant forward speed. This model was partially validated against flight data and demonstrated its ability to reproduce VRS entries. But while this model is able to correctly capture the drop of vertical speed, questions still arise about the representativeness of the vertical speed response due to a collective pitch increase as well as the ability of this model to well represent the helicopter behaviour during recovery techniques.

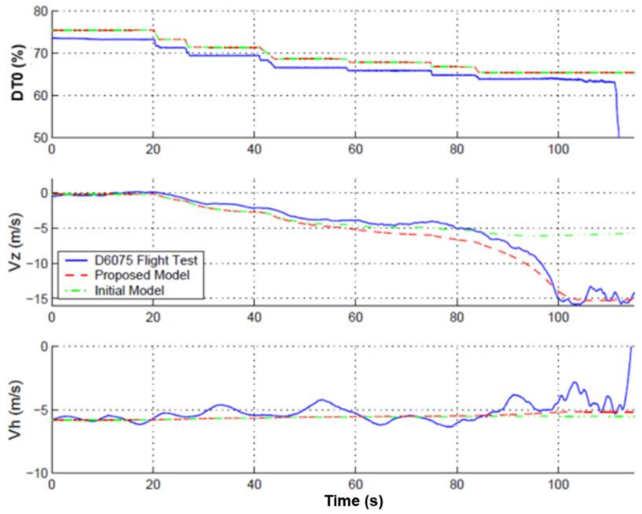

Fig. 2. ONERA induced velocity model ability to reproduce VRS entry

3.2. ATR VRS model description

Another VRS model, part of the official release of the HOST code has been also assessed in this paper. Contrary to the ONERA model, it is not based on an adapted induced velocity model in descent but on an artificial rotor thrust reduction.

Indeed, in most of the training simulators, VRS is reproduced by an artificial drastic decrease of the rotor thrust if the helicopter enters a predefined VRS domain (defined in terms of forward and vertical speeds) as illustrated in Fig. 3.

In this model, a pre-defined percentage of lift loss is set and applied depending on the speeds seen by the rotor with respect to a predefined VRS domain. The major disadvantage of this approach remains the need of experimental data and/or pilot evaluations to tune the different parameters defining the VRS domain. If this model can emulate a VRS entry, the question of its ability to reproduce some characteristics of the phenomenon remains open, as well as the representativeness of recovery techniques.

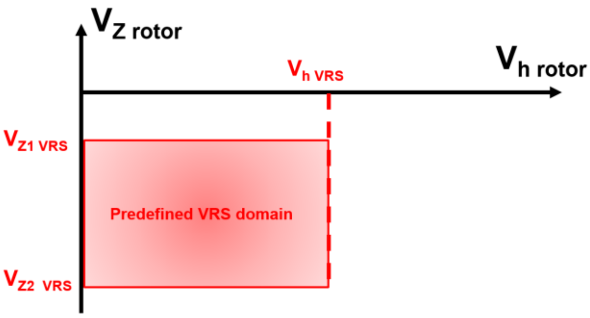

Fig. 3. ATR VRS model domain

In addition to the thrust reduction, cyclic efficiency reduction can be set while pitch and roll angle variations are generated in order to represent the characteristic increase of vibrations felt during the VRS phenomenon.

Following parameters were set during this study, but could be later tuned or adapted:

- Percentage of thrust reduction: 60 %
- Low threshold of cyclic efficiency: 5 %
- Vh VRS: 10 kts
- VZ1 VRS 1: -850 ft
- VZ2 VRS 1: -3250 ft

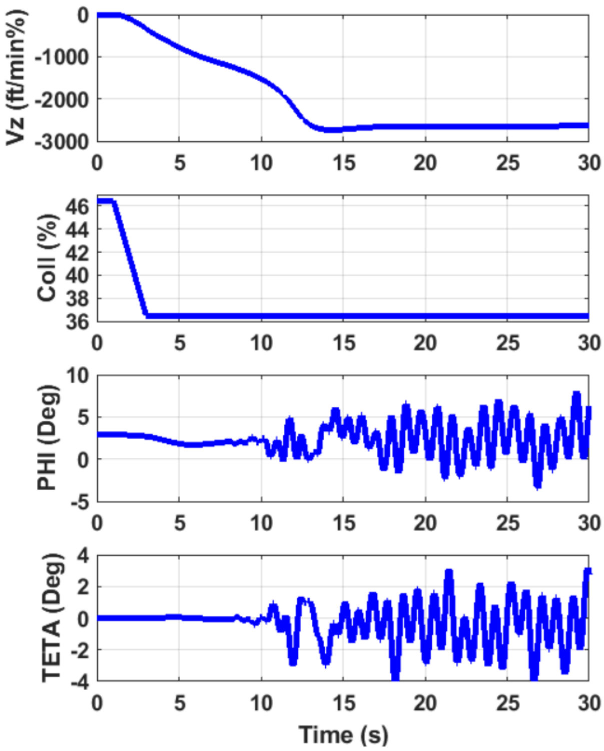

Fig. 4. ATR VRS model inducing pitch and roll angle variations

Shown in Fig. 4, representing a VRS entry through the reduction of the collective in off-line simulation, the model generates periodic pitch and roll angle variations of relatively large amplitudes: ± 5° on roll, ± 3° on pitch. If this clearly indicates a change in the helicopter behaviour to the pilot, one will see further in the paper that these oscillations are not representative of the VRS phenomenon, at least for the two types of helicopter studied, and even prevented to properly assess the Vuichard recovery technique in the ONERA simulator.

3.3. Flight test campaigns description

Preamble: the two pilots who were involved in the flight test campaign had a training flight on the Vuichard recoveries by Mr Vuichard himself. They were then only able to train and calibrate their actions during the harmonization flights on Dauphin helicopters. Even if they also flew 2 to 3 test flights on Fennec helicopters (during the first part of this campaign), they were thus less familiar with the Vuichard recovery method, which should be taken into account.

As a reminder, the two objectives of the tests were:

- to refine the characteristics of the VRS domain, especially to identify the premises of VRS and the VRS in itself on the type of aircraft flown for this test campaign;
- to evaluate the Vuichard recovery technique in comparison with the conventional procedure.

These two objectives focus on two different phases of the VRS:

- The first objective involves the entries, i.e. the conditions in which the helicopter can enter into a VRS and the observations made during such a state.
- The second objective is dealing with the exit, and the efficiency of the technique used to recover from a VRS.

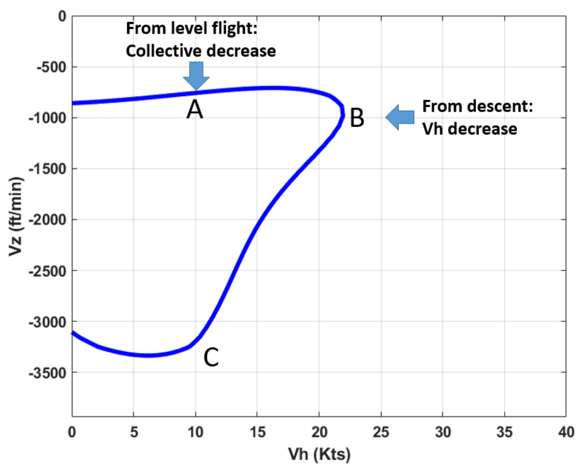

Fig. 5. Estimated Fennec VRS Domain (ONERA criterion)

The VRS domain can be divided into three main zones, as illustrated on Fig. 5.

- The “upper boundary” ➔ Zone A
- The “knee” ➔ Zone B
- The “lower boundary” ➔ Zone C

This study included entries through the A and B boundaries. The C boundary (lower part) of the VRS domain does not match any operational conditions, and was therefore not investigated as an “entry” boundary. Nevertheless, it corresponds in fight to the stabilisation of the vertical speed after VRS entries from the upper boundary or the knee.

During harmonization flights, several parameters were noticed to have an influence on the time to enter VRS for similar flight conditions, such as the dynamics of the power reduction. In order to avoid the influence of unwanted parameters on the results, the following actions were taken to improve the repeatability of entry manoeuvres, and to ensure the validity of the comparisons between both recovery methods for similar entry conditions.

First, two test pilots were trained by M. Vuichard to ensure they were adequately performing the Vuichard recovery manoeuver. They also flew harmonization flights together to calibrate their movements and avoid any discrepancy. They were the only evaluators involved in this test campaign. When only one of them was available for a flight, he was the single evaluator during the flight, and another DGA-EV pilot was present as a safety pilot.

Secondly, the action on the collective stick was “standardized” by decreasing the power rapidly to a torque of about 50% (slightly above the power level under which VRS was entered on the Fennec in the test conditions), and then wait a few seconds. If the aircraft did not enter VRS, the power would then be decreased slowly towards 20% torque.

3.3.1. Recovery techniques description

- The Vuichard recoveries were performed, as recommended by Mr Vuichard, by using the available power, that is to say the higher power that could be applied without exceeding the aircraft limitations, while simultaneously using the cyclic stick to reach a roll angle of -20° (toward the left) maintained during one second and the foot pedals to maintain the heading. After about one second, the roll angle was brought back to zero. Since a parasite nose-down motion resulted in a tendency to increase the forward speed during the last part of the recovery, some test points were performed trying to fight this parasite effect and to come back to hover as soon as possible, and others by accepting this forward speed and focusing on recovering a positive vertical speed ;
- The inversed Vuichard recoveries were performed similarly to the Vuichard recoveries, but with an exit on the “wrong side” at a roll angle of +20°, i.e. toward the right for the Fennec and Dauphin. This idea was to assess the consequences of either a mistake by the pilot, or of the impossibility to perform a Vuichard recovery toward the left, due to an obstacle for example;
- The classical recoveries where performed using an optimal power setting, balancing between the positive effect of power on recovery performances, and the workload typically associated to watching the aircraft limitations at higher power settings.

On a total of 177 validated runs, 146 recoveries were performed in a fully developed VRS and 31 at VRS premises. Following figures provide the flight test runs distribution.

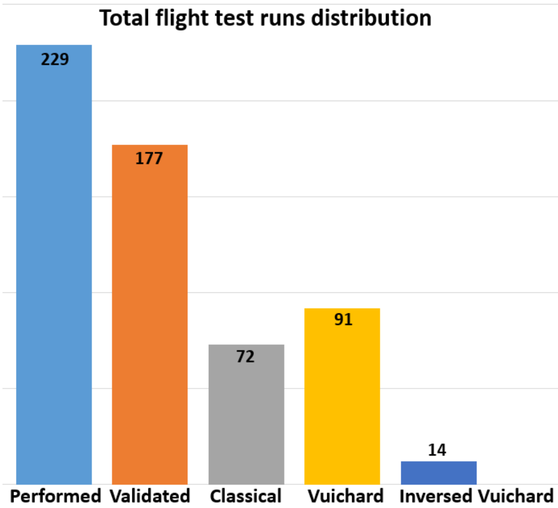

Fig. 6. Total flight test runs distribution

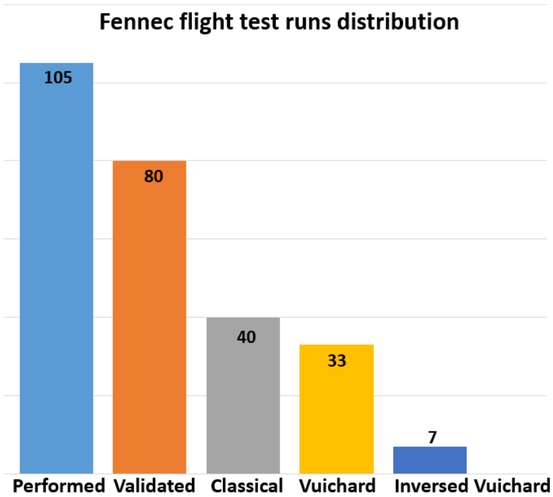

Fig. 7. Fennec flight test runs distribution

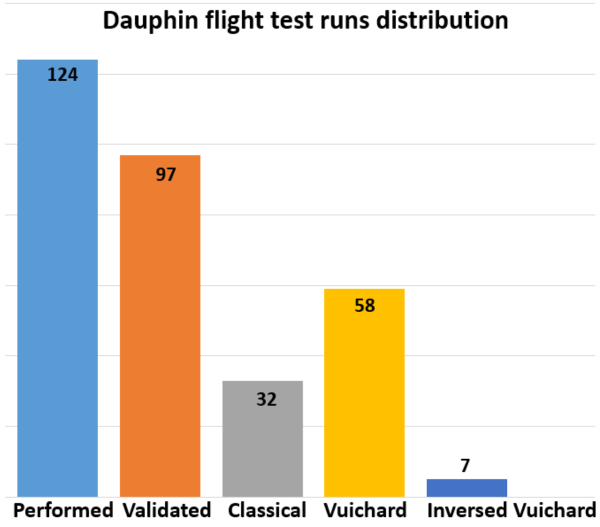

Fig. 8. Dauphin flight test runs distribution

3.4. Differences with previous flight test campaigns

In the previous flight test campaigns performed by DGA-EV and ONERA, Zone B was determined in the same way than in the current project, i.e. by decreasing the airspeed in a pre-established descent. But as shown in Fig. 2, VRS entries were mostly realized through successive slight collective decreases in order to "slowly" reach the VRS domain from the upper boundary.

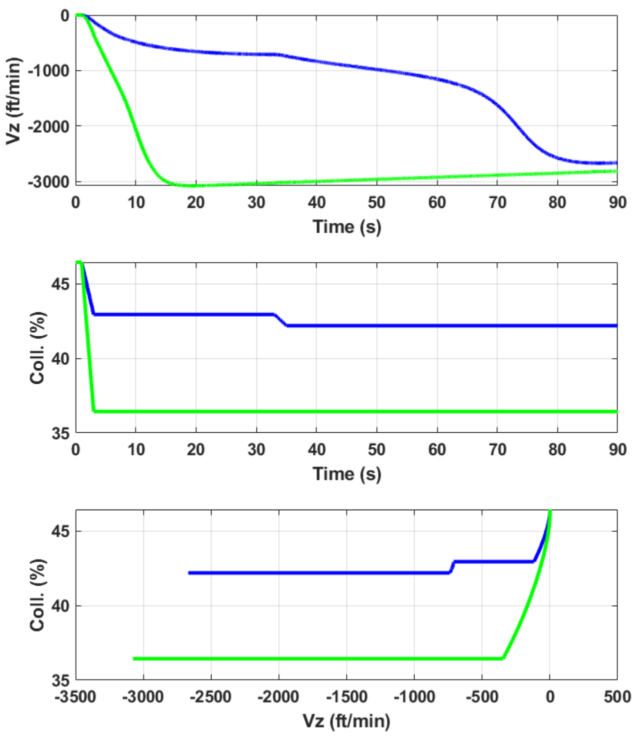

Fig. 9. Two collective decreases strategies

In this project, pilots were lowering the collective more rapidly to be sure to enter VRS at each run and more quickly, enabling the realization of more test cases in a flight. The difference between both strategies is represented in the Fig. 9 thanks to two simulations.

The blue curve corresponds to slight successive decreases of the collective, leading to a VRS entry at around 60 s, and a vertical speed Vz of -1175 ft/min. The green curve corresponds to the strategy applied during the EASA flight tests, with a large collective decrease directly leading to the lower boundary of the VRS domain (Vz = -3000 ft/min). In these conditions, determining the VRS entry is almost impossible through the simple analysis of the characteristic Vz drop, as this can be seen on the figure. Nevertheless, this determination can be done, in some cases, through the analysis of other parameters (accelerations, sideslip measurement device, vibration measurement, etc.).

An interesting point can be outlined from the third subplot where Vz is plotted with respect to the collective level. One can see that very different levels of collective can lead to an almost identical vertical speed which is not the case in normal flight (level, climb, moderate descent), where a level of collective corresponds to one vertical speed. This characteristic will be later detailed and comparisons with flight test data will be done.

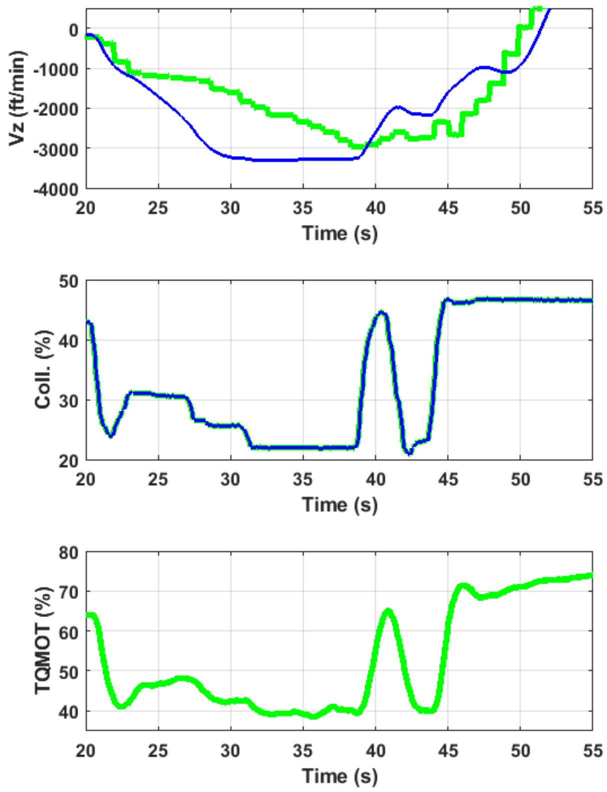

Fig. 10. Collective increase in fully developed VRS

In addition, once in a supposed fully developed VRS, pilots were increasing the collective to verify that there was only a very limited impact on the vertical speed. This effect was already verified in previous flight tests and is a characteristic of the phenomenon. Fig. 10 represents the Vz, collective level and engine torque during a fully developed VRS flight on the Fennec helicopter. The green curves are the flight data while the blue ones are the results of a simulation. The strategy to follow flight test data in a simulation will be explained in the next chapters. During the simulation, the variations of the collective are followed, the variation of the vertical speed being the result of the OA VRS model in this case. As there's no engine model in the HOST version used at ONERA, the engine torque is not available through simulation. After the collective decrease at 20 s to enter VRS, the pilot managed to reach and hold a torque of 40%. It can be observed that the collective variations after the first decrease slowed the increase of the rate of descent during the flight test. The helicopter reached a Vz of -3000 ft/min in 18 s while in simulation, a Vz of around -3200 ft/min is reached in 10 s. At 38.5 s, the pilot increased the collective by 22.6% in less than 2 s and then re-decrease it to its initial level. This collective increase had almost no impact on the helicopter vertical speed (392 ft/min of variation) while this generates of variation of 1272 ft/min in simulation. This flight test run clearly shows that once in a fully developed VRS, an increase of the collective is inefficient but doesn't worse the situation. The OA VRS model is not representative of the vertical speed response due to a collective variation. Then at 43.5 s, the pilot performed a classical recovery by increasing the collective and pitching down the helicopter to increase the forward speed.

Finally, compared to the previous flight test campaigns, tests runs were performed with either a recovery initiated at the first signs of VRS (recovery at vortex premises), or once the VRS was fully established. The efficiency of the recovery techniques when performed either at premises or in fully established VRS, and all associated analyses will be presented in the final EASA report in November. Nevertheless, comparisons between flight test data and simulations will be shown later in this paper and discussed.

3.5. Strategy to follow flight test data

The flight mechanics code used at ONERA, while implementing official helicopter data packages from Airbus Helicopters, hasn't been tuned to match flight test parameters as this is done for training simulator. Using as inputs the recorded pilot controls would lead to the divergence of the simulation, especially in such complex manoeuvres, and specific strategies have been applied to follow flight data.

Thus, pre-developed flight control laws or auto-pilot modes were used to either follow the helicopter airspeeds or attitudes. A Translational Rate Command law (TRC) has been tuned to follow the longitudinal and lateral speeds of the helicopter in simulation, or to impose pre-defined speeds for parametric studies.

When the goal is to reproduce recovery techniques from flights, the controls are switched to an Attitude Hold mode (ATT) enabling to follow the helicopter pitch and/or roll angles. The heading was managed by either the TRC or the ATT mode.

As the vertical speed drop is the major characteristic of the VRS phenomenon, the vertical axis was always left free. Therefore, same collective variations were applied in simulation than in flight, the absolute values being different.

Considering this control strategy, as it has to be noted that the results of the simulations are therefore not representative of the helicopter response except on the vertical axis, the other axes being constrained by a flight control law or an auto-pilot mode.

4. RESULTS

While 4 flights were performed on both Fennec and Dauphin helicopters, the comparisons between simulations and flight tests were only done on the Fennec model.

4.1. Recovery techniques

In the following sub-chapters, recovery techniques have been simulated in different test cases and compared to flight data. As a reminder, the purpose here is not to evaluate the different recovery techniques through the use of simulation, but to assess the capability of real-time VRS models to match with main flight parameters and VRS symptoms and effects.

4.1.1. Classical recovery in fully VRS with and without collective increase

The classical technique is generally described as hereafter:

- Reduce collective;
- Ease cyclic forward to adopt a nose down attitude
- Maintain heading by using the pedals
- When the airspeed is above translational lift, increase collective to maximum continuous power to climb

But Airbus Helicopters currently recommends (as described in SIN-3123-S-00) this recovery by:

- increasing the power if necessary,
- pushing the cyclic forward for 1-2 s until a speed of 20-30 kts is reached,
- and then adjusting the pitch to come back to an horizontal attitude

Having a common and unique definition of the classical technique during the flight test campaign was thus mandatory. While pilots considered that reducing the collective during the recovery would have detrimental effect on the loss of height (defined as the height difference between the initiation of the recovery manoeuvre and a null or positive vertical speed) and the overall efficiency of the procedure, some test cases were performed with a delayed increase of the collective (in fact, once the helicopter was already out of the VRS).

Fig. 11 shows flight parameters (longitudinal airspeed Vx, Vertical speed Vz, Collective, Pitch angle Teta and Altitude) during two runs, where the helicopter entered in a fully developed VRS. Data are synchronized, and the recovery procedure starts at 11 s with a pitch down attitude to increase the forward speed. On one case, the collective was increased simultaneously (red curve) while it was maintained at its current position in the other case (blue curve).

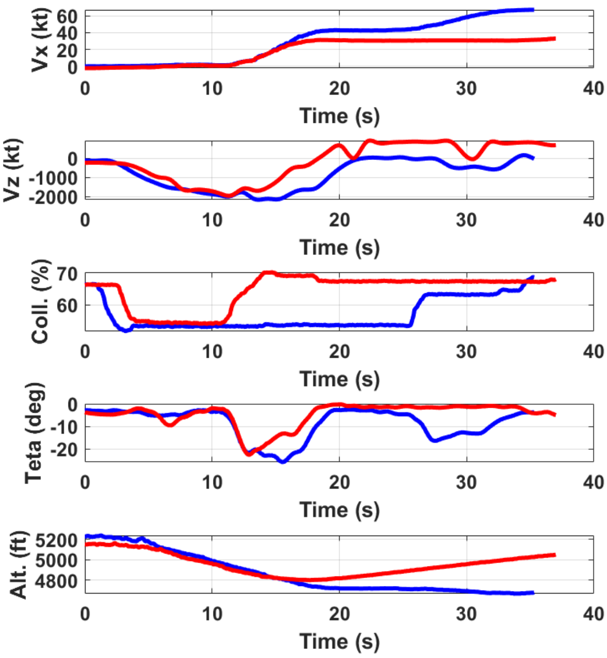

Fig. 11. Classical recovery with and without collective increase

The pitch down angle applied is comparable in both cases and the forward speed increases similarly. But the recovery time (defined as the time necessary to reach a null vertical speed after the recovery manoeuvre start) is 8.5 s in the first case, 11.5 s in the second one. The resulting loss of height being respectively 114.4 ft and 225.64 ft.

In a general manner, an increase of the loss of height is observed when the collective is not increased during the classical recovery. In flight, the observed average loss of height without collective increase is 283.92 ft, while it is 184.56 ft with a collective pull-up. While not experimented, there's no doubt that a reduction of the collective would lead to higher loss of altitude. That's why collective increase was considered during the entire flight test campaign on both helicopters.

In Fig. 12, a comparison is done between flight data (green curve) and two simulations. The blue dotted line corresponds to a simulation where collective variations applied in flight are exactly reproduced. As already shown, following the same collective variations lead to much higher vertical speed (more than -3000 ft/min compared to -2000 ft/min in flight). The blue solid line shows the results of a simulation where the collective variations have been modified to better match with the vertical speed. In simulation, the loss of height with similar collective variation is around 452 ft while it is 272 ft with adapted collective variations. It was equal to 225.64 ft in flight.

It has to be noted that, while the pitch down is produced later in both simulations, forward speeds are comparable to the flight test.

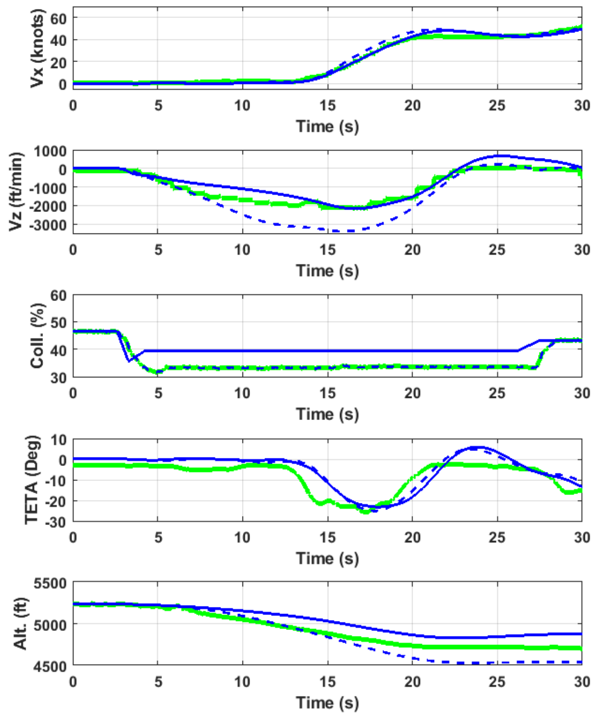

Fig. 12. Classical recovery without collective increase

The same comparison is done in the following Fig. 13 where the collective increase is applied simultaneously with the pitch down attitude.

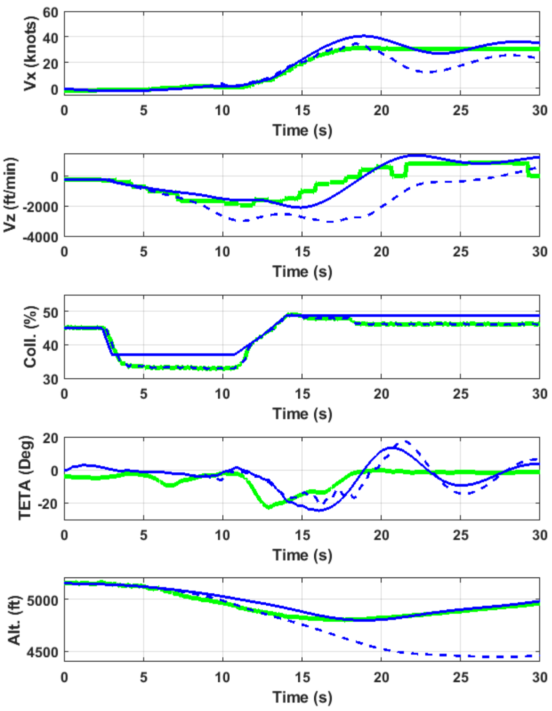

Fig. 13. Classical recovery with simultaneous collective increase and pitch down attitude

Here again, adapting the collective variations is needed to better reproduce the Vz drop. It can be seen that the pitch down performed at the same time than the collective increase (at 11s) lead to a slight descent rate re-increase in both cases while this is not observed in flight. In simulation, the loss of height with similar collective variations is around 490 ft while it is 203 ft with adapted collective variations. It was equal to 114.4 ft in flight.

4.1.2. Classical recovery at VRS premises

The following Fig. 14 shows comparisons between simulations and flight test where the recovery was initiated at VRS premises, corresponding to a vertical speed of -1200 ft/min. Once again, it is necessary to adapt the collective inputs to better follow the vertical speed of the flight. In that case, the height loss is 84 ft, compared to 70.22 ft in flight and 193.2 ft in simulation with same collective variations.

The analysis of the flight test data showed that the vertical speed at the onset of the recovery is one of the most important influencing parameter on the height loss. The higher the initial vertical speed (in absolute value), the higher the height loss on average, with a significant dispersion. On average, the recoveries at VRS premises tend to occur at lower initial vertical speeds, and therefore induce smaller height losses, which was expected.

Simulations are able to reproduce the effect of the initial Vz (at recovery initiation) on the height loss. Nevertheless, it requires the tuning of the collective pitch to better match with flight data.

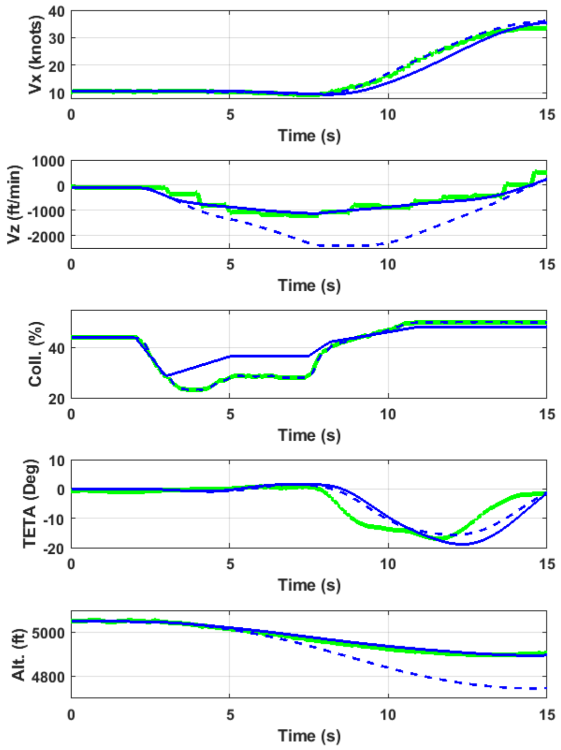

Fig. 14. Classical recovery at VRS premises

4.1.3. Classical recovery in decelerated flight

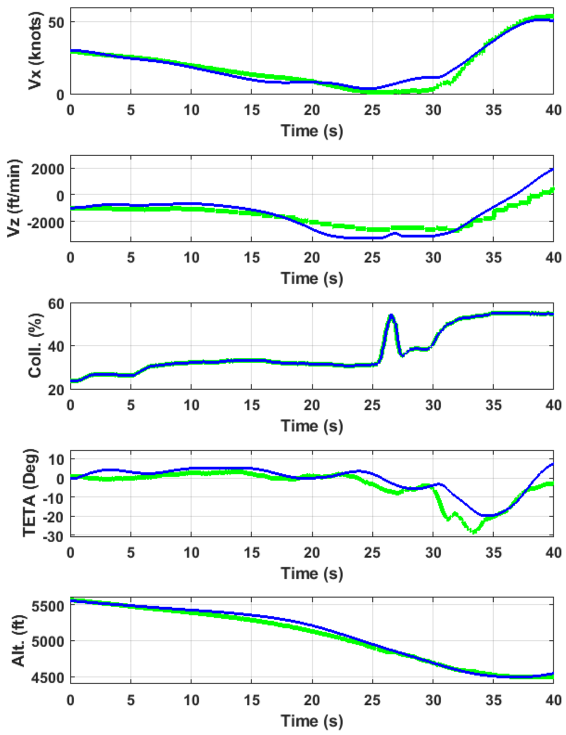

Fig. 15. Classical recovery in decelerated flight

A total of 16 VRS entries in decelerated flights were performed to determine the “knee” of the VRS domain and to evaluate the recovery techniques in such condition.

Fig. 15 shows the comparison of flight data and a simulation where the collective variations reproduce the ones performed in flight. If the flight parameters are mostly well captured in simulation, it is interesting to see that the collective increase at 27 s, to evaluate if the VRS is fully developed, has a very limited impact on the vertical speed in flight while it is larger in simulation. In this case, there was no need to modify the collective to match the flight data. The height loss in flight was 203.48 ft and a very comparable value is obtained in simulation: 198.6 ft.

4.1.4. Vuichard recovery in fully VRS

A Vuichard recovery is simulated in the following Fig. 16. In order to enter the VRS as in flight, modifying the collective inputs is still mandatory here. Instead of applying a pitch down attitude, a roll angle variation on the left is performed as the helicopter rotor turns clockwise. As recommended by Mr. Vuichard, the power increase is applied prior or at least simultaneously with the lateral cyclic action.

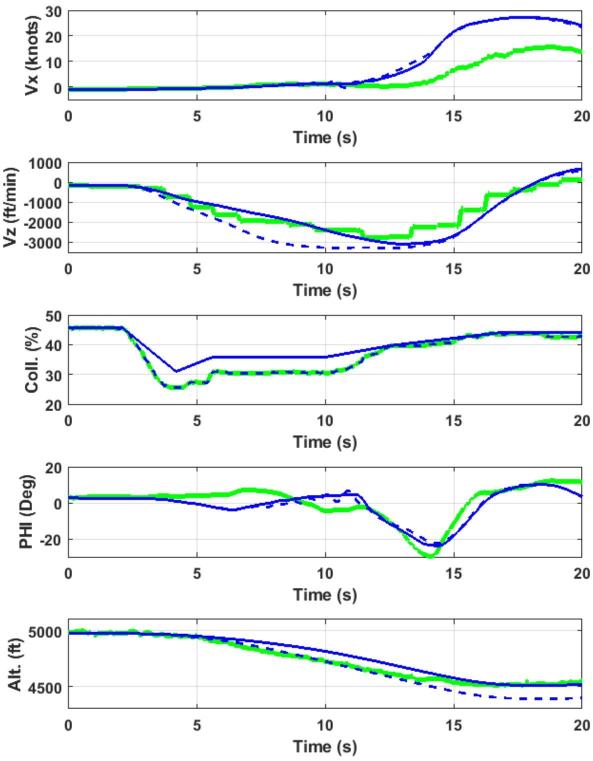

Fig. 16. Vuichard recovery in fully developed VRS

The height loss observed in flight was 153 ft while it is much higher (306 ft) in simulation, even with the corrected collective. Additional tuning of the collective could improve the simulation results. In addition, as shown in Fig. 17, the pitch angle variations are higher in simulation than in flight, certainly contributing to a longer duration of the descent rate increase and thus, a higher loss of height. Intrinsic cross-couplings are affecting the helicopter response in flight, increase the pilot workload, and have to be well captured by the flight mechanics models in such procedures.

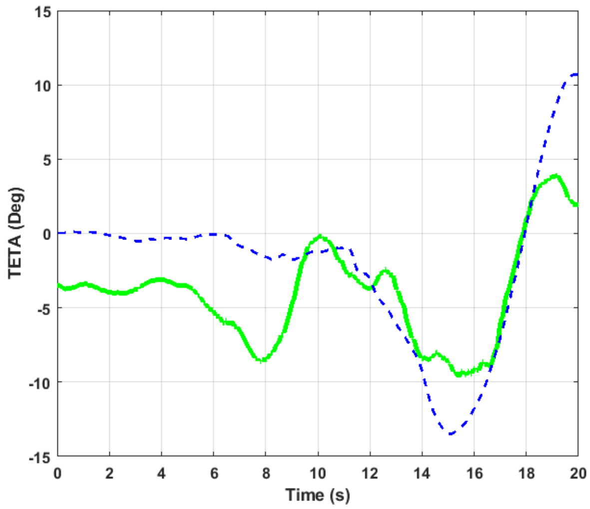

Fig. 17. Pitch angle variation during Vuichard recovery

4.1.5. Vuichard recovery at VRS premises

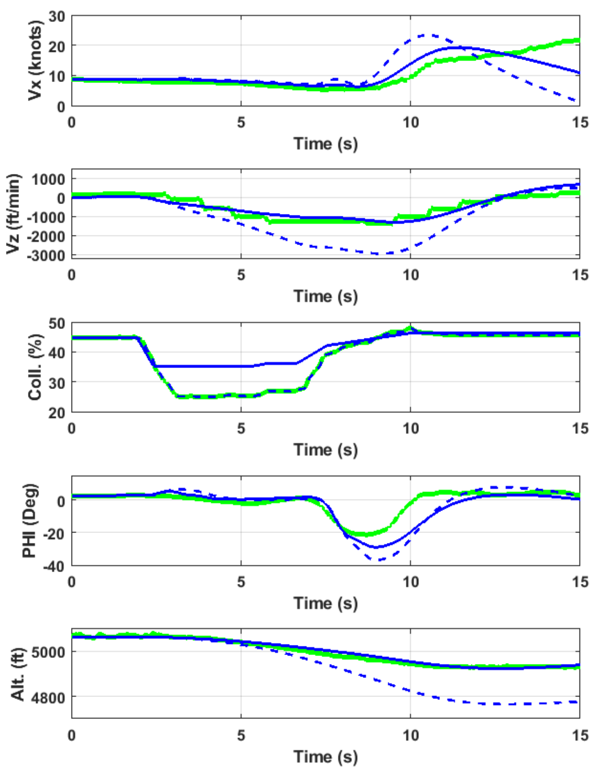

Fig. 18. Vuichard recovery at VRS premises

The Vuichard recovery has also been evaluated when performed at the VRS premises as this can be seen on Fig. 18. Following the flight test collective lead to larges discrepancies between simulation and flight data, but the adaptation of the collective variations largely improve the simulation results. An ATT mode is used in the simulation to follow helicopter attitudes. Nevertheless, the maximum roll angle variation is higher (+30°) in simulation than in flight (+20°) and it takes a longer time to be brought back to 0°.

As already experienced with classical recoveries, the efficiency of the procedure is much higher when fulfilled at VRS premises, with a limited loss of height in flight (67.27 ft) and 92 ft in simulation.

4.1.6. Inversed Vuichard recovery in fully VRS

During the entire flight test campaign, 14 inversed Vuichard recoveries were performed. 7 on the Fennec and 7 on the Dauphin. A comparison is shown in Fig. 19 between flight data from a Fennec run and a simulation. In this example, the simulated collective corresponds to the collective variations applied in flight. As recommended, the roll angle variation, done on the right here, is simultaneously done with the collective increase at 5.8 s.

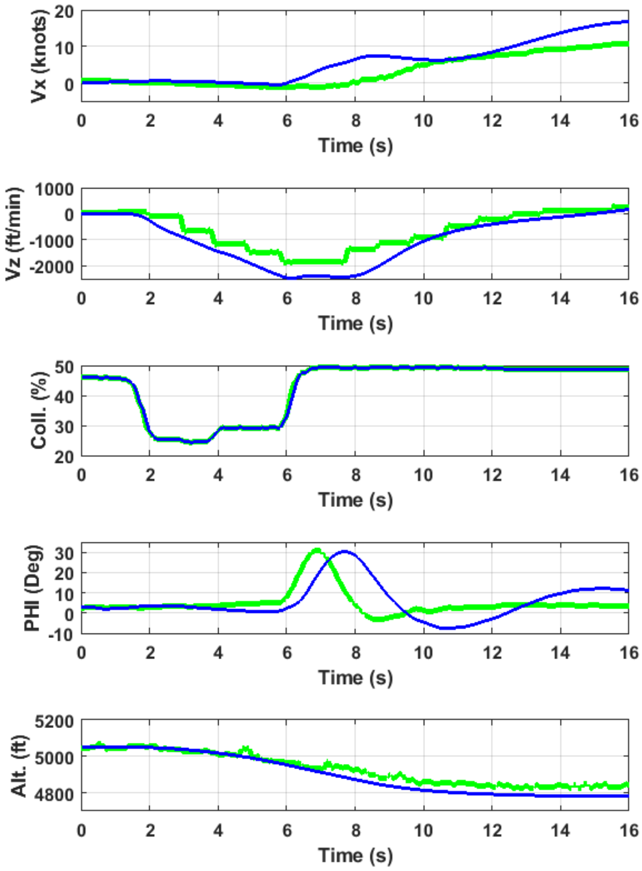

Fig. 19. Inversed Vuichard recovery at in fully developed VRS

Contrary to what is observed in the previous case, the roll angle variation is the same in simulation than in flight (+30°), but a delay of 1 s can be seen with here again a longer time to come back to 0°. While simulated response of the vertical speed, and roll angle variation could be improved to better match with flight data, the loss of height are relatively similar with respectively 141 ft in flight and 179 ft in simulation.

4.1.7. Summary of comparisons between simulation results and flight data

Comparisons between flight test data and results of simulation are showing relatively good agreement. The OA VRS model is able to reproduce VRS entries and recovery techniques in different conditions. The loss of height, which remains the major effectiveness criteria for evaluating recovery techniques, is comparable to the one observed in flight, but this requires a tuning of the collective pitch effect on the vertical axis.

As observed in flight, the flight conditions at which the recovery is initiated have a very large effect on the performances of the applied procedure, especially the vertical speed. For that reason, even before trying to simulate (and even more, to evaluate) recovery techniques through simulations, it is necessary to ensure that the VRS entry is well reproduced by the flight mechanics code, i.e. in the same vertical speed conditions.

In our case, this imply to modify the level of collective applied in simulation compared to the one applied in flight. A large part of the discrepancy between level of collective and resulting vertical speed is certainly due to the induced velocity model used. As explained in chapter 2.1, the OA VRS model modifies the induced velocity in descent. As a result, this changes the relation between collective pitch and vertical speed. As this will be detailed later, VRS is characterised by the generation of a hysteresis in the collective pitch/Vz curve. This is characterised by the possibility to reach different vertical speeds with the same level of collective.

In Fig. 20, trim computations have been done and comparisons between different induced velocity models in vertical flight are presented, from a climb speed of +1000 ft/min to a descent rate of -3500 ft/min. The basic model is the Meijer-Drees model in red curve, largely based on the momentum theory. This simple model is known to be erroneous for descent rates corresponding to VRS down to wind-mill brake state, and provides a monotonous relation between collective and vertical speed. It means that a collective value always implies a vertical speed in any (steady) conditions (considering all other parameters such as airspeed or mass being constant).

The OA VRS model modifies the induced velocity in descent which cause a change in the collective/Vz curve as this can be seen on the blue curve. Thus, the curve is similar to the momentum theory in climb and down to around -600 ft/min. But for higher descent rates, a hysteresis appears and the level of collective re-increases (as the induced velocity), to finally decrease down to very high descent rates, towards the autorotation and wind-mill brake state branch. In green on the figure, the ATR model also presents this hysteresis. Being also based on the Meijer-Drees model in these computations, the collective/Vz curve is similar to the momentum theory in climb and down to around -1000 ft/min and below -3100 ft/min. Between, the amount of collective is much higher than with the OA model, reaching nearly 80% at Vz=-2200 ft/min.

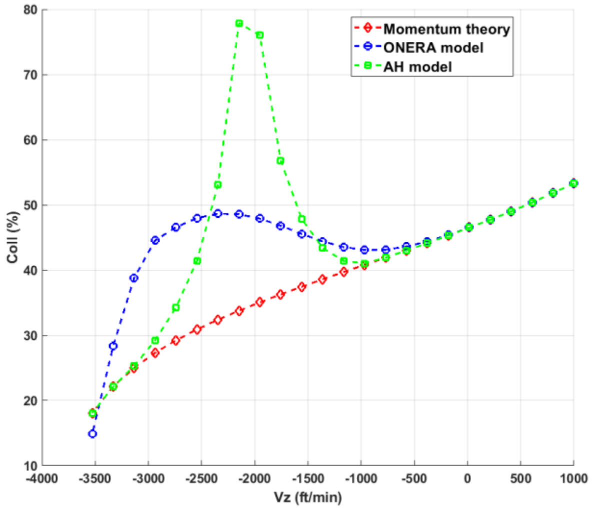

Fig. 20. Comparison of induced velocity models in descent

In addition to the potential difference in the control mixing between pilot collective grip and blade pitch between the flight mechanics model and the real helicopter, this can explain why, depending on the collective decrease applied at the beginning of the run to quickly reach the VRS, results of simulations and flight test can be different depending on the induced velocity model used. For instance, starting from hover (Collective = 46%), a reduction to 30% would lead to a RoD of around -3200 ft/min with the OA model, -2950 ft/min with the ATR model, and -2600 ft/min with the momentum theory. This also clearly shows the effect of the induced velocity model on the resulting vertical speed, and the need to have tuned models in such flight conditions.

Linked to the representativeness of the induced velocity model, the effect of a collective increase in fully developed VRS is also different between simulation and flight and a parametric study based on simulations will be detailed in next chapters.

As already mentioned, as using the “real” pilot controls as simulation inputs is almost impossible, a strategy had to be developed to follow helicopter attitudes. In our case, a tuning of the ATT mode gains could be done to better follow the attitude variations.

Helicopters are well known to present cross-couplings in every axis. Nevertheless, cross-coupling considerations are certainly not sufficiently taken into account during studies on VRS and more particularly recovery techniques evaluations, that all require large and rapid attitude variations. The strategy used during these off-line simulations prevented the analysis of these effects as helicopter attitudes were not resulting from pilot controls. Nevertheless, simulator trials performed by one pilot and further detailed showed the lack of representativeness of the flight mechanics code in this domain. This project has been an opportunity to fully assess the impact of these couplings on the pilot's workload and the effectiveness of the recovery techniques, while helicopters operated by DGA-EV have semi-rigid rotors on which cross-coupling effects are certainly minored compared to rigid rotors.

Finally, pilot’s workload can obviously not be assessed through off-line simulations. Flight test analyses clearly outline the large impact of the pilot’s workload on the efficiency of the recovery manoeuvres. Both manoeuvres involving inter-axes actions and cross-couplings effects, reducing the workload generally improves the efficiency of recovery. Taking into account the pilot’s workload is thus mandatory to properly evaluate these techniques, which here again requires representative flight mechanics code and real-time piloted simulations.

4.2. Off-line parametric studies

4.2.1. Collective efficiency in fully developed VRS

As introduced previously, comparisons with flight data showed a larger effect of a collective increase on the vertical speed in simulations.

In order to investigate this effect, several off-line simulations (see Fig. 21) were performed with both OA and ATR induced velocity/VRS models. A large collective decrease was first done as in flight to reach VRS, and different collective increases were then applied. First, 10% increase (solid line) and 20% increase (dashed lines) during a limited time, and finally a maintained 20% of collective increase (dotted lines).

As previously explained thanks to Fig. 20 showing trim computations, the Vz response according to collective variation is highly dependent on the induced velocity/VRS model used. With the OA model, applying and maintaining a large increase of collective leads to overpass the hysteresis and high positive vertical speeds can then be reached.

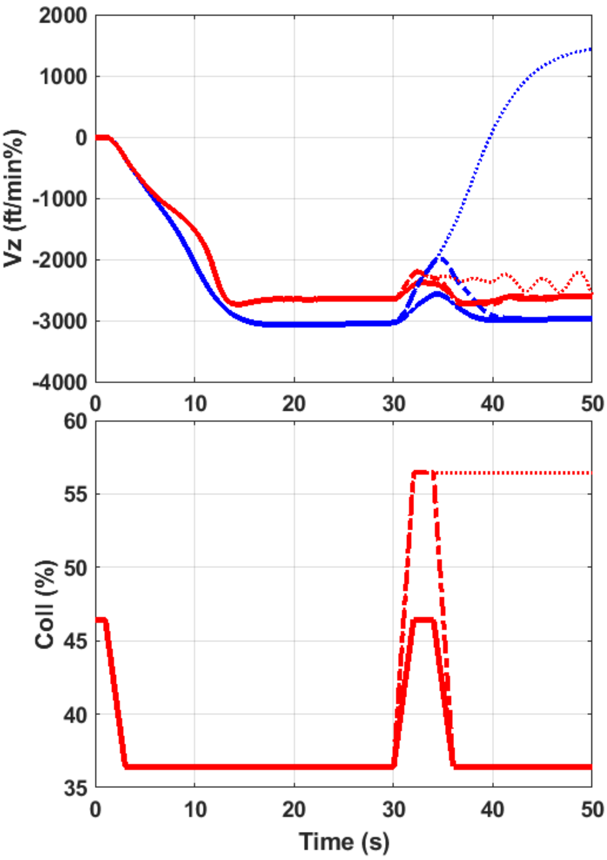

Fig. 21. Comparison of collective increases in fully developed VRS

This is not the case with the ATR model, as generating a much stronger hysteresis curve. Only an application of more than 80 % of collective would allow to overpass the hysteresis which will never be done in real flight, as this would certainly cause over-torque. As done in flight, a temporary collective increase generates a temporary reduction of the descent rate in both cases, while it is too strong with the OA model as shown in the previous comparisons with flight data. The ATR model is more representative, inducing a much limited response of the vertical speed and even more, preventing its re-increase with a maintained collective pull-up.

4.2.2. Collective efficiency at VRS premises

Once in a fully developed VRS, raising the collective has a limited effect of the vertical speed. This characteristic was used in flight to verify that the VRS was effectively established. But during some runs, this verification was done at relatively low rates of descent.

First, and as a reminder, the Fennec VRS domain, established during a previous flight test campaign led by the EPNER School in 2003 [11], is shown in Fig. 22. While a dispersion of the points can be seen, VRS premises can be considered occurring for RoD between -600 ft/min to -1400 ft/min, from vertical descent to 20 kts of forward speed.

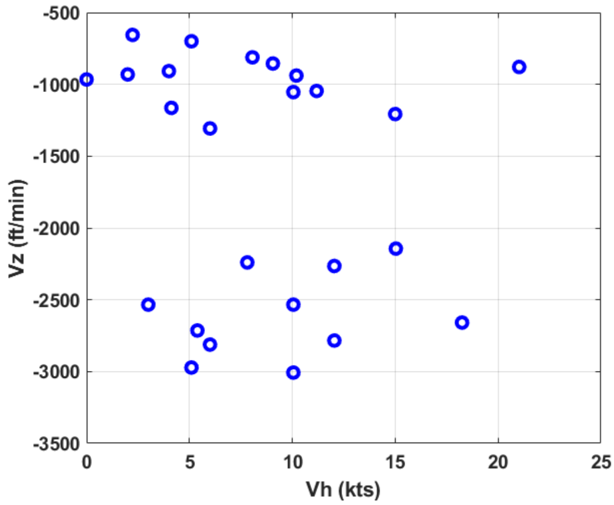

Fig. 22. Fennec VRS domain

In Fig. 23, a test run on the Fennec helicopter is shown, where a collective increase was performed at 41 s without any action on the other axes. The vertical speed at that moment was -1560 ft/min, the longitudinal speed around 6 kts and the lateral speed was null, corresponding to VRS premises. While no other action on the cyclic was done, this collective increase had a major effect on the rate of descent which decreased to zero in less than 8s. The resulting total loss of height being of 76.3 ft only.

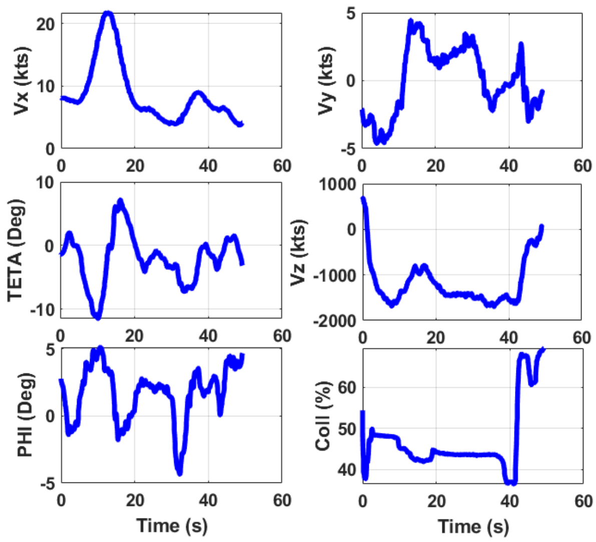

Fig. 23. Effect of collective increases at VRS premises in flight

Some simulations were done in order to evaluate the capability of the VRS models to reproduce this outcome.

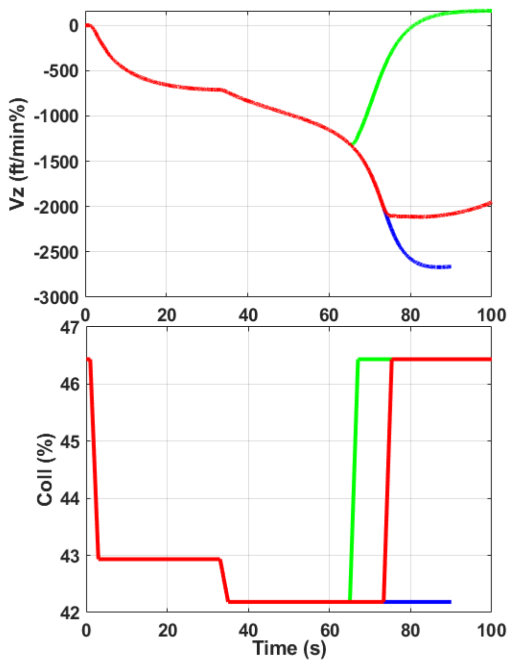

Fig. 24. Effect of collective increases at VRS premises in simulation with the OA VRS model

The OA VRS model was first assessed in Fig. 27 showing, in blue curve, successive collective decreases leading to a fully established VRS and where no action is undertaken to exit. A vertical descent is performed in this example. The green curve shows a collective increase up to the initial collective value, performed at a RoD of -1307.8 ft/min (at 65 s). As this can be seen, the drop of Vz is just initiated, well corresponding to VRS premises. The effect on the vertical speed is immediate, the hover being reached at 80.8 s and a total loss of height of 158.4 ft. Another simulation was done (red curve) where the collective increase was applied at a higher descent rate (-2075 ft/min). In this condition, the same collective increase is not able to recover from VRS, stabilising the descent rate to -2000 ft/min.

The same simulations were realized with the ATR VRS model are shown in Fig. 25 and very comparable results can be noticed.

When no action is undertaken, the RoD stabilised at around -2500 ft/min for a collective decrease of -7%. When the collective is increased at 48.9 s, at a RoD of -1300 ft/min, the VRS is exited and hover is reached in 15.7 s (in 15.8 s with the OA model), with a loss of height of 114 ft. As observed with the previous VRS model, a collective increase at a RoD equal to -2000 ft/min doesn't allow to recover, the RoD stabilising at -2400 ft/min.

As a conclusion, both VRS models are able to reproduce recovery if power increase is carried out at VRS premises. In these conditions, as observed in flight, the only application of a collective increase seems sufficient to get out of the phenomenon. Nevertheless, this must not to be considered as a fully-fledged recovery technique and an increase of the speeds (longitudinal or/and lateral) remains mandatory to be sure to get away from the VRS domain. But this demonstrates that, very close to the VRS domain, at VRS premises or even in case of VRS suspicion, the first action to take is certainly a raise of collective pitch.

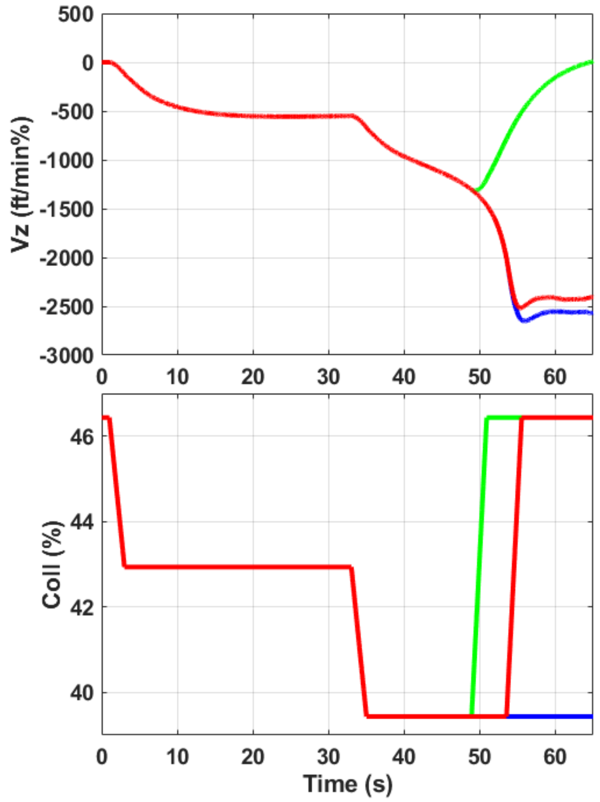

Fig. 25. Effect of collective increases at VRS premises in simulation with the ATR VRS model

4.2.3. Collective vs Vertical speed

Already observed in previous flight test campaigns and discussed in [11], the relation between level of collective and vertical speed is modified in VRS. In Fig. 26, the blue points are taken from the first Fennec flight performed in the framework of this project, and correspond to the level of collective plotted with respect to the vertical speed in "stabilised" conditions. Actually, these points are plotted when during a run, and function of time, the variation of the vertical speed is lower than 75 ft/min, the collective variation is lower than 1%, and for forward speeds between -5kts and +5kts. While not exactly corresponding to trim computations as shown in Fig. 20, these points correspond to short-time stabilized flight conditions.

One can clearly see that below -1000 ft /min down to -3000 ft/min, the collective/Vz curve is no more monotonous and several very different descent rates can be reached with the same level of collective.

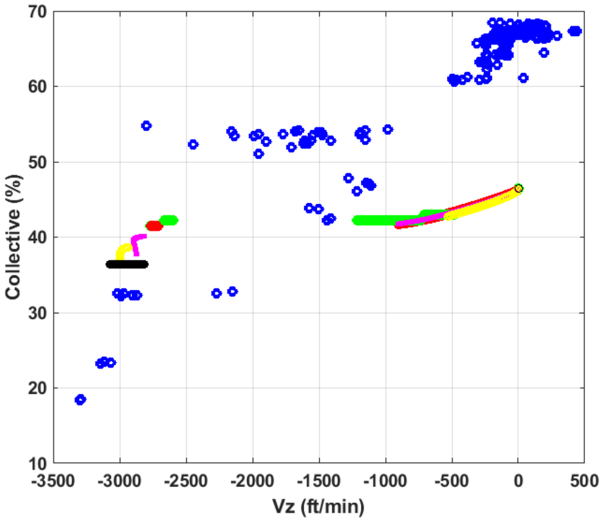

Fig. 26. Collective vs VZ in stabilised flight test cases

In climb and vertical descent down to -500 ft/min, a dispersion exits but the average collective/Vz curve is monotonous. This is also the case for descent rates higher than -3000 ft/min.

The different coloured plots in the figure have been generated in the same conditions but processing the data from 5 different simulations. Except the bias in terms of collective level (20% in hover), the same characteristic is observed, i.e. several achievable vertical speeds for a given level of collective.

Considered as a criterion, this characteristic could be also used, as the Vz drop, to define the VRS domain of a helicopter.

4.3. Delayed collective application during recoveries

As discussed in subchapter 3.1.1, an increase of the loss of height is noticed when the collective is not increased during the classical recovery.

In Fig. 27, four simulations were completed to evaluate the effect of anticipated (blue curve), simultaneous (red curve), or delayed (by 10s for green curve, 20s for magenta curve) increase of the collective in a classical recovery in vertical descent and fully developed VRS. For all cases, the pitch angle variation applied was -10°.

The respective loss of height observed in simulations are given hereafter:

- Collective –5 s before pitch down: 308 ft
- Collective 0 s with pitch down: 352 ft
- Collective +10 s after pitch down: 412 ft
- Collective +20 s after pitch down: 413 ft

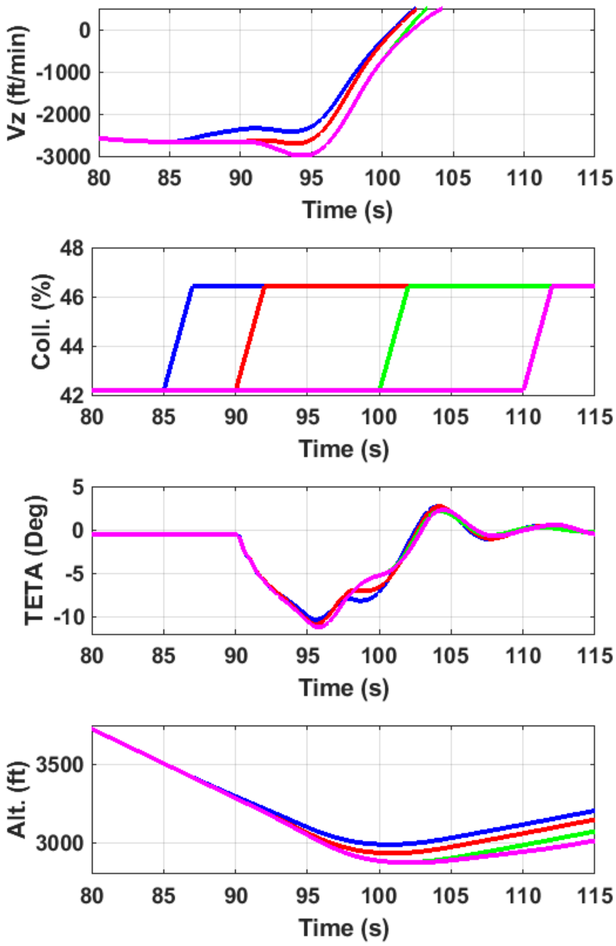

Fig. 27. Effect of delayed increase of the collective on height loss in classical recovery

In this case, an anticipated collective increase improve the efficiency of the procedure but this result must be taken with reservations. It has been previously shown that an increase of the collective in VRS has an over-estimated effect on the vertical speed when using the OA induced velocity/VRS model.

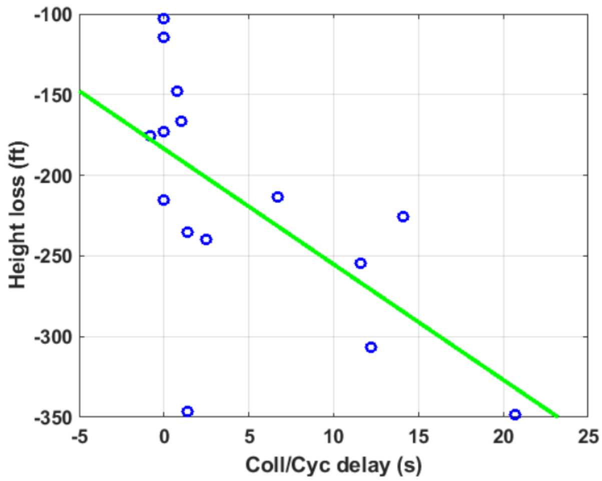

Fig. 28. In-flight effect of delayed increase of the collective on height loss in classical recovery

As this can be seen again on the Fig. 27, when applying the collective increase 5 s prior to the pitch down attitude, the descent rate is already reduced when the recovery manoeuvre is initiated, leading to a reduced loss of height. In flight, such an effect would probably not be observable, or highly minored.

As generally measured in flight, the height loss increases as a function of the delay in collective increase. Fig. 28 shows the measured loss of height in flight (Fennec) with respect to the delay between collective increase and action on the longitudinal cyclic during classical recoveries in vertical descent and fully developed VRS. A dispersion of the points can be observed, but the fitting curve clearly highlights this trend.

4.4. Pitch attitude in classical recovery

A quick parametric study has been performed to evaluate the effect of the pitch angle variation on the loss of height during a classical recovery in vertical descent. Three simulations are shown in Fig. 29 where the minimum pitch angle reached were -12°, 19° and -27.5°. The corresponding height loss measured are 313.6 ft, 314.3 ft and 352.6 ft.

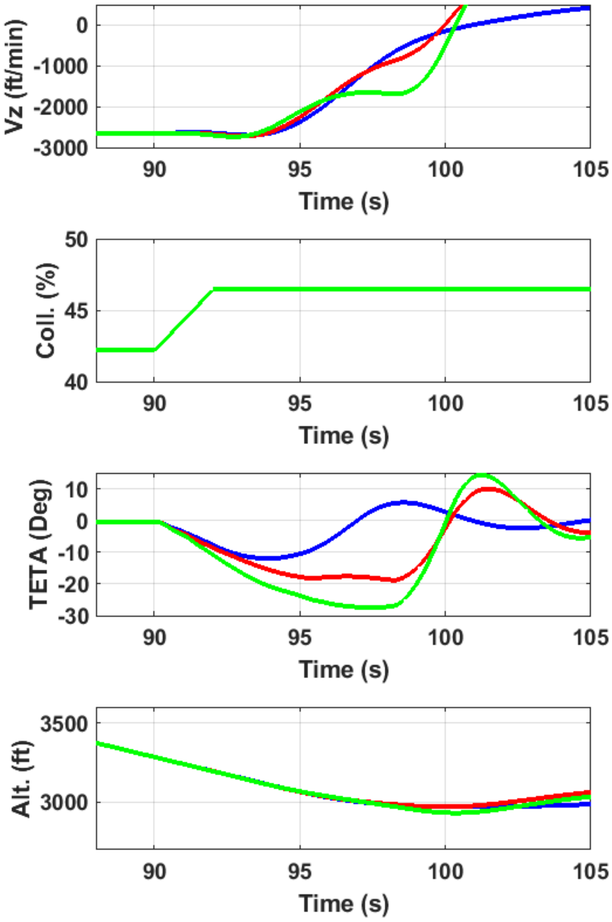

Fig. 29. Effect of the pitch angle on the height loss

As well as in simulation, the analysis of the flight data showed that, in classical recoveries and fully developed VRS, higher nose down attitudes tend to worsen the height loss.

Fig. 30 shows the minimum pitch angle reached during classical recoveries in fully developed VRS performed on the Fennec. While a large dispersion can be noticed, the linear fitting curve seems to show that higher nose down attitudes effectively tends to worsen the loss of height.

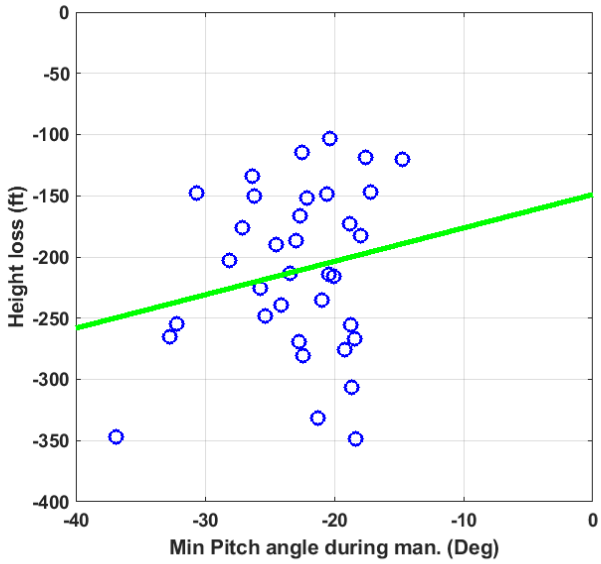

Fig. 30. Height loss depending on minimum pitch angle in classical recoveries in fully VRS

4.5. Roll attitude in Vuichard recovery

A comparable parametric study has been done for the Vuichard technique. The effect of the roll angle value reached during the Vuichard recovery has been evaluated in vertical descent and fully VRS. Fig. 31 shows three simulations were the minimum roll angle reached during the manoeuvre (starting at 90s) were -6.8°, -17.3° and -23.6°. The respective loss of height being 351 ft, 245 ft and 242 ft, indicating that the loss of height is here reduced as the roll angle is increased.

The effect of the roll angle on the height loss for Vuichard recoveries in fully VRS is shown in Fig. 32, where the minimum roll angle reached during the Vuichard procedure in all corresponding Fennec runs are plotted. Contrary to the classical manoeuvre, and despite the important dispersion, there seems to be a decrease of the height loss with the roll angle.

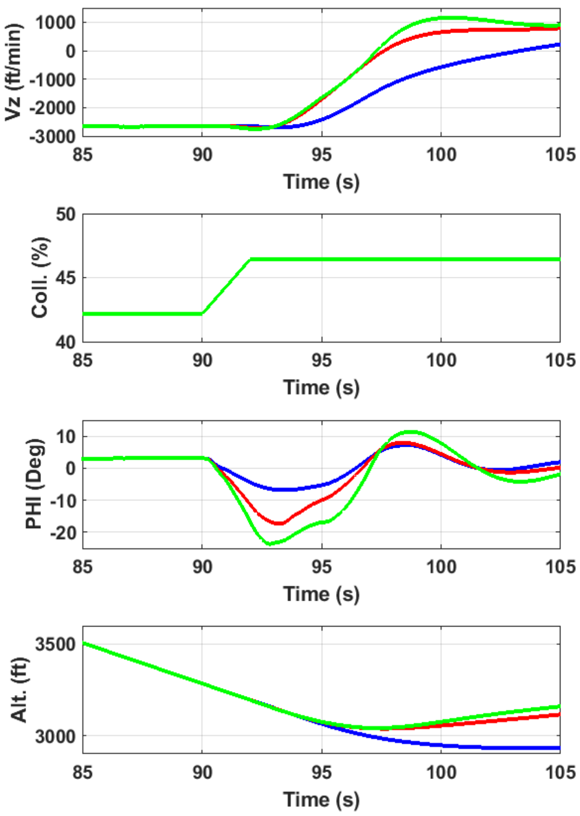

Fig. 31. Effect of the roll angle on the height loss

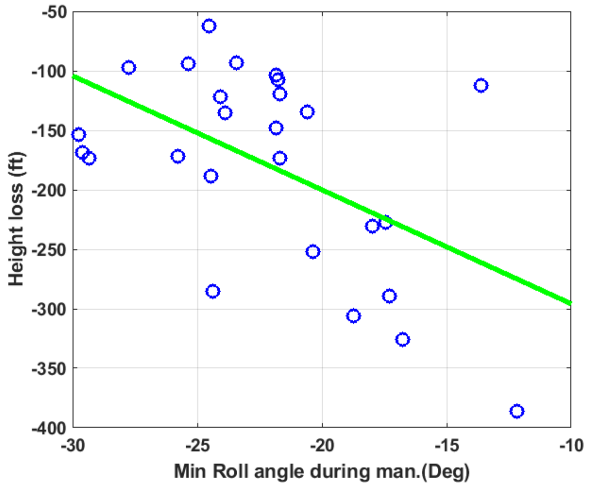

Fig. 32. Height loss depending on min. roll angle in Vuichard recoveries in fully VRS

4.6. Off-line simulation of dynamic VRS

The so-called "dynamic vortex", occurring in dynamic manoeuvres such as quick stops, large attitude variations at low speeds or flares, is insidious and can catch even very experienced pilots. Performing dedicated flight tests to deeply analyse these flight cases is a challenge, and carrying out numerical studies is just as difficult, if not more.

13 decelerated flight cases and 2 quick stops were performed on the Fennec, 1 decelerated test case on the Dauphin.

Some examples of dynamics vortex entry realized in off-line simulations are given hereafter.

Fig. 33, already shown in [11], represents the results of a simulation performed with the Dauphin model. Starting from a 10 kts airspeed (Vx), a collective decrease is done at 2 s, inducing a rate of descent Vz of -1000 ft/min. While close to the VRS domain, the rate of descent stabilises. Then, at 22 s, a quick stop manoeuvre is initiated at constant collective level by an increase of the pitch angle TETA (from 7° to 12°) thanks to the ATT mode. The change in airspeed seen by the rotor lead to VRS, easily highlighted by the drop of Vz. The rate of descent finally stabilises at -3250 ft/min.

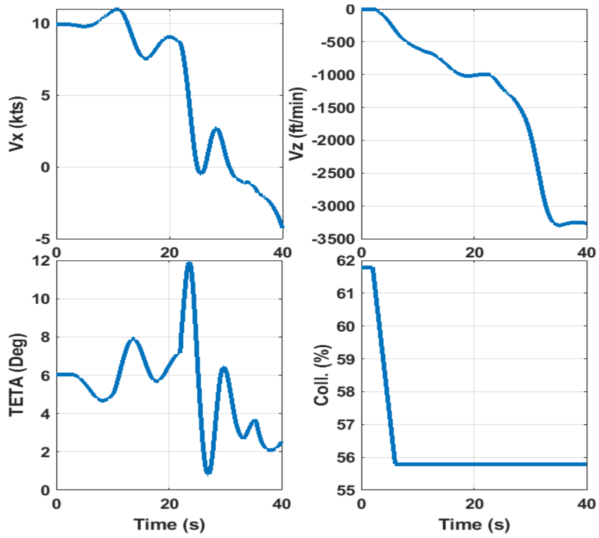

Fig. 33. Dynamic vortex entry through off-line simulation of pitch attitude variation

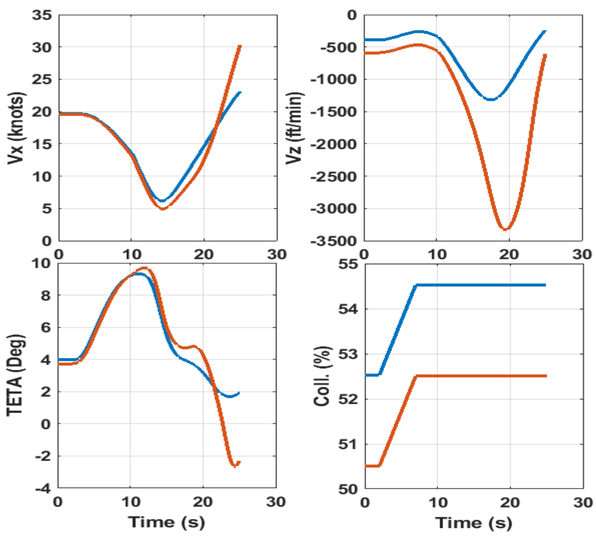

Fig. 34. Dynamic vortex entry during nose-up to level attitude variation

Another simulation of a dynamic vortex is given in the following Fig. 34, where a "level-off" is done from a pitch-up attitude realized from an initial airspeed of 20 kts and an established rate of descent of around -400 ft/min for the blue curve and -590 ft/min for the red curve. At the transition from nose-up to level, the resulting rate of descent reaches -1250 ft/min in the first case, while the helicopter enters VRS in the second case, before existing it due to the increase of the forward airspeed. The same behaviour would be observed in rear flight, from a nose-down attitude to level.

This clearly demonstrates that performing pitch variation at low speeds can lead to VRS even if the rate of descent seems safe with respect to VRS, here around -600 ft/min.

5. SIMULATOR TRIALS

Previous simulations demonstrate the ability of the off-line tool to simulate VRS entries and recoveries, in different flight conditions or with different "pilot" controls. We can therefore assume that, using a flight mechanics code validated against flight data, this simulation tool could be used to explore a greater number of flight cases with a good degree of confidence and as already shown, could be adapted to the realization of parametric studies. Nevertheless, real-time piloted simulations remain necessary to study such manoeuvres, by enabling a pilot to experience and evaluate the realism of the helicopter behaviour and the workload needed to proceed to recovery manoeuvres.

One of the pilot who participated to the flight test campaign performed simulator trials on the ONERA research simulator PycsHel. Both Fennec and Dauphin helicopter models were tested, as well as the two VRS models. These simulator trials were only focussed on vertical descent cases, in which Vuichard and classical recovery techniques were assessed. The number of test cases with respect to the type of recovery technique realized and VRS model used are summarized in Table 1:

DAUPHIN		Recovery	
		Classical	Vuichard
VRS Model	ONERA	3	2
	AH	6	

FENNEC		Recovery	
		C	V
VRS Model	ONERA	4	3
	AH	6	4 (all invalid)

Table 1: Number and type of recovery manoeuvres performed in simulator

A major limit to these evaluations has to be raised: as for off-line simulations, the real-time simulator only features an ideal engine model offering an unlimited power and a constant rotor RPM. Thus, the workload associated to the management of the torque/power cannot be evaluated.

As shown in Fig. 4, the ATR VRS model generates periodic pitch and roll angle variations of relatively large amplitudes. As well as being considered unrealistic by the pilot, roll oscillations lead to PIO on the lateral axis, leading to the impossibility to properly perform the Vuichard recovery in the simulator as illustrated in Fig. 35.

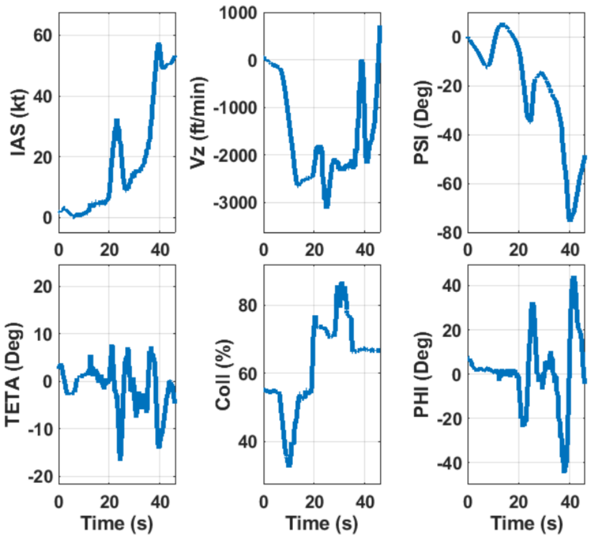

Fig. 35. Impossibility to assess the Vuichard technique

Indeed, at 20s, the recovery manoeuvre was initiated through a simultaneous increase of the collective and a roll variation to the left. But the ATR VRS model inducing roll variations, the pilot always experienced difficulties to reached and hold a desired roll angle. Pitch attitude variations due to this VRS model increased the workload and cross-coupling effects. Four runs were done on the Fennec model, all considered unusable. Thus the Vuichard manoeuvre wasn't tested on the Dauphin model.

5.1. simulator trial results

Table 2 provides, for both helicopters, the averaged loss of height and recovery duration depending on the recovery technique practiced, the VRS models and compared to the ones measured in flight. As indicated, simulator and flight test cases are corresponding to vertical descents and a recovery manoeuvre initiated in fully developed VRS.

In simulator, the averaged loss of heights are much greater than those observed in flight for both helicopters. This can be certainly explained by the fact that, as already outlined, the collective decrease lead to higher descent rate in simulation. Recovering from higher descent rate contributing to increase the loss of height.

Vertical descent - Fully developed VRS					
DAUPHIN	Simulator			Flight tests	
	Classical		Vuichard	Classical	Vuichard
	OA	AH	OA		
Average loss of height (ft)	408,54	461,26	270,47	236,4	252,65
Average Recovery duration (s)	8,74	10,42	7,57	8,52	13,71

Vertical descent - Fully developed VRS					
FENNEC	Simulator			Flight tests	
	Classical		Vuichard	Classical	Vuichard
	OA	AH	OA		
Average loss of height (ft)	342,94	435,84	286,69	217,77	185,5
Average Recovery duration (s)	8,71	11,54	9,22	9,85	9,85

Table 2: Average loss of height and recovery duration in simulator compared to flights

Height loss and recovery time are always higher with the ATR VRS model inducing much more workload and parasitic effects due to attitude variations.

On Fennec, recovery time is very comparable between flight tests and the OA model for both techniques, as well as on Dauphin for the classical manoeuvre. On Dauphin, recovery duration is much lower with the OA model for the Vuichard technique, which can be explained by the lack of representativeness of the flight mechanics model in terms of cross-couplings and associated attitude changes faced in flight, and the reduced workload in simulator, where power margins and helicopter limits exceedances had not to be managed. Nevertheless the averaged loss of height is comparable with the one in flight.

Only considering flight test data, it has to be noted that in these conditions, the averaged loss of height is slightly lower during a classical rather than a Vuichard recovery on the Dauphin, while this is the opposite on the Fennec. Recovery durations are the same on the Fennec, while it takes a longer time to recover on the Dauphin when performing the Vuichard technique. This will be detailed in the next sub-chapter.

In addition to the pilot feedback, a specific data processing has been carried out on pilot controls in order to estimate the pilot control activity during the recovery procedures. Thus, Table 3 provides the calculated standard deviations of the pilot commands during the recovery on the three axes in simulator compared to flights.

In flight, standard deviations are always higher during the Vuichard recovery. If this can be expected on the lateral axis, it can also be shown on the longitudinal and yaw axes, highlighting the strong cross-couplings involved in this manoeuvre. Interestingly, the standard deviation on the lateral cyclic is higher than on the longitudinal during the classical procedure on the Dauphin.

DAUPHIN	Simulator			Flight tests	
	Classical		Vuichard	Classical	Vuichard
	OA	AH	OA		
std Lateral (%)	6,13	9,93	15,48	7,75	12,63
std Longitudinal (%)	9,25	18,42	9,25	5,99	8,68
std Pedals (%)	7,87	4,56	7,87	4,53	5,8

FENNEC	Simulator			Flight tests	
	Classical		Vuichard	Classical	Vuichard
	OA	AH	OA		
std Lateral (%)	6,64	12,62	15,03	6,41	10,6
std Longitudinal (%)	14,79	20,33	7,07	7,54	8,75
std Pedals (%)	6,26	3,8	12,37	5,72	6,65

Table 3: Controls activity in simulator compared to flights

In simulator, the ATR VRS model implies greater control variations on all axes, which is due to the generated attitude variations.

On both helicopters, the OA VRS model gives consistent results where the maximum standard deviation is observed on the predominant axis of the manoeuvre. On the Fennec, the standard deviation on the yaw axis is much higher during the Vuichard technique. This can be potentially explained by a reduced efficiency of the pedals in the simulator observed at the beginning of the trials. A better calibration could improve the results by lowering the need of pedal activity. It has to be noted that this controls activity is not directly comparable to the pilot workload, while contributing to it. But this can provide objective criteria on the parasitic effects occurring during the manoeuvres as this will be detailed in the next chapter.

5.2. Pilot feedback on simulator trials

On both helicopter models, a specific tuning of the pedals efficiency was requested at the beginning of the trails. In addition, the collective/yaw coupling was considered not representative.

When entering VRS, a reduction of effectiveness of the cyclic pitch controls may be experienced in flight, resulting in a decrease of the control power on both longitudinal and lateral axes. A reduction of effectiveness of the pedals can also be observed, leading to yaw motion. In order to represent these effects, the ATR VRS model offers the possibility to reduce the efficiency of the cyclic but this parameter has to be carefully set. At the beginning of the trials, the efficiency was too reduced to properly perform any recovery procedure.

In a general manner, pitch and roll oscillations generated by the ATR model were considered unrealistic, leading to PIO on both axes, more exacerbated on the lateral one. This was impossible to target a predefined attitude angle (especially the roll angle). Thus, the Vuichard recovery manoeuvre was made particularly difficult to execute, even though numerous parasitic effects were not rendered.

Classical manoeuvres performed with the OA model were generally more realistic than the Vuichard manoeuvres, and more corresponding to what can be experienced in flight.

On Dauphin, and during Vuichard manoeuvre, the Fenestron/rear elements effects are not present in simulation. In flight, much more actions on pedals are needed and parasitic effects are more important as this will be detailed hereafter.

5.3. Focus on Vuichard recovery on Dauphin helicopter flight tests

One of the main lesson learned is that, in simulator, cross-couplings induced during Vuichard recovery, especially on the Dauphin, are not captured.

Indeed, while trained the pilots encountered in flight difficulties and a high workload during Vuichard recoveries due to the strong and sudden attitude changes encountered during the recovery, which had to be corrected by actions on all 4 control axis (cyclic longitudinal and lateral, collective, and foot pedals). The feedback was similar to what was observed on the Fennec flights, but with even worse parasitic effects and attitude changes (very likely due to the effect of the Fenestron and large rear aerodynamic elements during the lateral translation), and less power margin, which results in a higher workload and more risks to exceed the aircraft limitations.

The following Fig. 36 shows Dauphin helicopter parameters during a Vuichard recovery performed in fully developed VRS and highlighting the major difficulties encountered by the pilots in this flight test campaign.

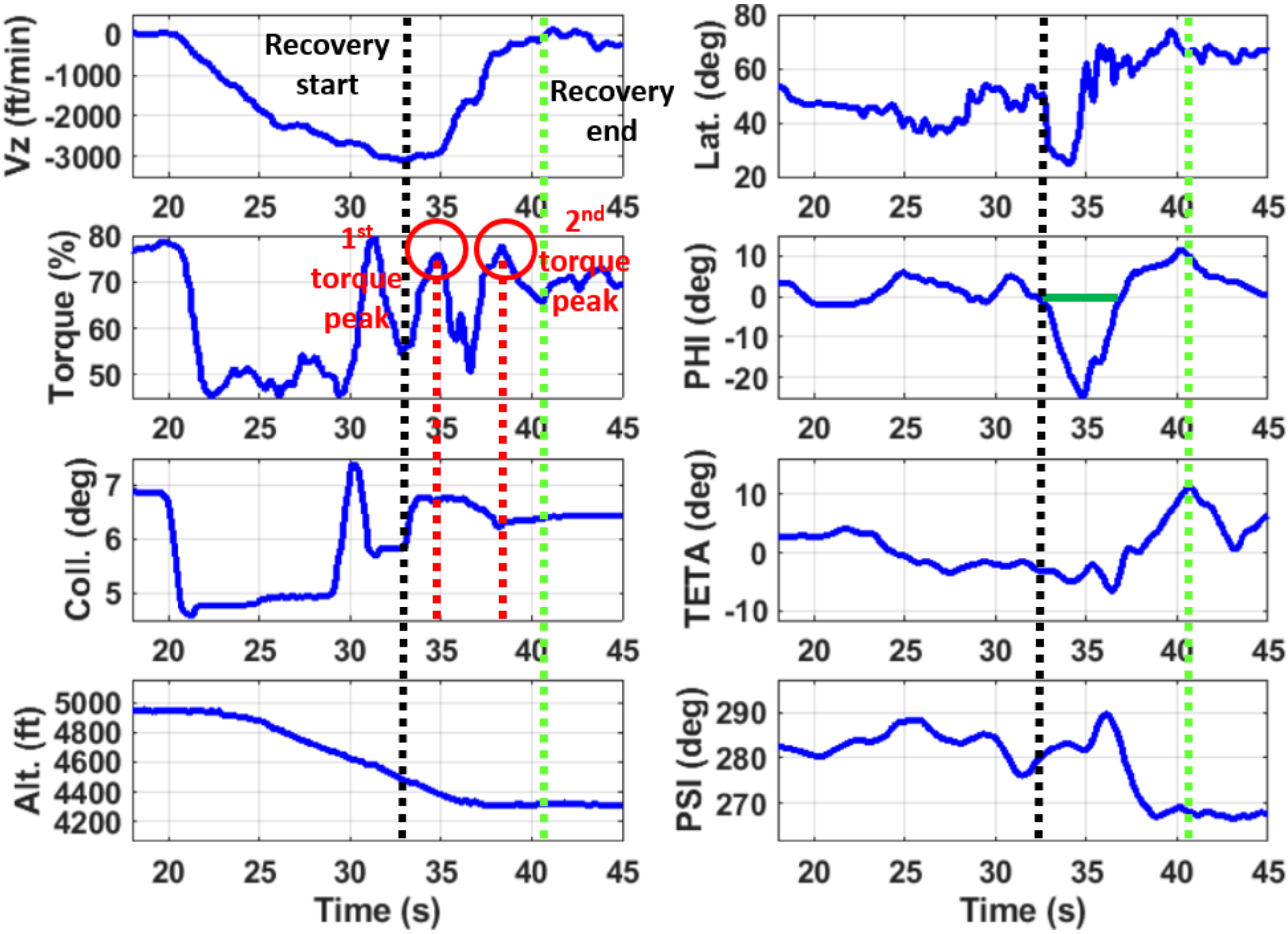

Fig. 36. Example of Vuichard recovery on Dauphin from established VRS

Going more into details:

- During the initial increase of power and simultaneous lateral translation toward the left, a parasitic yaw motion toward the left was observed, which had to be countered by an action on the right foot pedal to maintain heading. A parasitic nose-down motion was also noted at the end of the translation, which had to be countered by an action on the longitudinal cyclic. Meanwhile, fluctuations in power (torque and NG) had to be closely monitored to avoid exceeding the limitations: for this reason the pilots kept a margin compared to the requirement to use "all the available power". A first power peak was usually observed in the middle of the roll;
- When putting the rotor back to an horizontal position, actions were required on the cyclic (both axis) and foot pedals to maintain the heading and keep the helicopter flat, while closely monitoring the power level to manage a second peak of power. As shown in Fig. 36, this second peak, often higher than the first, occurred despite slightly decreasing the collective, and was only caused by the actions on the cyclic and foot pedals to stabilize the aircraft attitudes. The parasitic yaw motion (likely due to the effect of the lateral speed on the fin/empennage/fenestron) was maximal at this stage: due to the proximity with the limit of authority on the right pedal and to the speed of these changes, heading changes of -20° on average and up to -50° were observed in flight, despite the pilot actions.

6. POTENTIAL IMPROVEMENTS AND PROPOSED RECOMMENDATIONS

As shown previously, both VRS models have advantages and disadvantages that are summarized hereafter.

ATR VRS model:

- It is based on a predefined VRS domain, requiring preliminary flight tests or a good estimation of the boundaries;
- Subjective artificial thrust and cyclic efficiency reduction factors have to be carefully set, and would certainly be different on each helicopter types;
- Good representativeness of the vertical speed response after power increase in fully developed VRS, due to the increase of the hysteresis observed on the collective pitch/Vz curve.
- Pitch and roll artificial oscillations are generated to emulate the increase of vibrations once in VRS. But the pilot considered them too strong and too periodic and thus, not realistic. These oscillations should be better tuned to represent vibrations felt in flight.

OA VRS model:

- Based on a modified induced velocity model in descent, it is supposed to be rather generic and doesn't require a predefined VRS domain;
- The relation between collective pitch and descent rate have to be improved. The maximum RoD reached in VRS after successive collective pitch decreases is comparable to flight data but the vertical speed response due to power increase is too strong.
- The induced velocity model should be improved to modify the collective pitch/Vz hysteresis curve. This could be done by modifying the maximum value of the induced velocity in descent.
- The model doesn't generate any vibration once in VRS. This feature was developed in the 2000s and should be re-studied. Vibration measurements were performed in some of the flights of the test campaign. The analysis of the amplitude and frequencies observed in VRS conditions could be used to develop a representative model.
- The only VRS symptom emulated is the drop of vertical speed, due to the change in the collective pitch/Vz curve. The reduction of power control is not taken into account and could be investigated in the future.

If there was no doubt at the beginning of this study that the VRS models could be improved, the lacks of the flight mechanics model were not expected or at least, were under-estimated. Indeed, particularly present on the Dauphin helicopter, severe cross-couplings were experienced in flight when performing a lateral recovery. Neglected cross-coupling and parasitic effects tend to highly reduce the required workload during simulator tests, contributing to (partially/greatly?) distort the results. Exacerbated on the Dauphin, different models may be the cause of these discrepancies. A study of the Fenestron model should be carried out, as well as the aerodynamic models of the rear elements such as the vertical fin or the horizontal empennage which is equipped with relatively large vertical fins on this machine. Investigations should be carried out to verify the aerodynamic polar curves and the generated forces and moment at very high angles of attacks as well as to ensure that empennage vertical fins are properly taken into account.

Following this study, some general recommendations can be drawn on the use of simulation models to study the vortex phenomenon and, more specifically, to evaluate the recovery techniques.

- A precise knowledge of the induced velocity/VRS model is requested to have an idea of the shortcomings and limitations of the modelling used. Preliminary validation is mandatory to later perform any evaluation;
- This preliminary validation should be focussed on the main VRS characteristics and most influencing parameters such as the ones presented in this paper;
- Off-line simulations can be used to partially validate induced velocity/VRS model and perform parametric studies, but results have to be considered with great caution;
- The control strategies (stabilisation or automatic control) required for off-line simulations can make cross-coupling and parasitic effects invisible;
- Finally, the great lack of off-line simulations is the impossibility to estimate the pilot workload during the manoeuvre. But workload has a major impact especially on recovery efficiencies. Developing a “pilot model”, and analysing the control activity required to achieve a manoeuvre could be a first step to fill this gap, but it’s not an easy task;
- Real-time piloted simulation are still mandatory to evaluate helicopter behaviour in VRS and associated recovery techniques. Nevertheless, simulator evaluations are useless without tuned and validated flight mechanics codes and VRS models;
- In addition, realistic and comparable levels of workload must be ensured in simulator trials against flights.

7. CONCLUSIONS

As part of the objectives of the “VRS-Helicopter Vortex Ring State Experimental Research”, the goal of this study was to evaluate the correctness of flight mechanics code and two different VRS models and reproducibility of recovery techniques. Off-line simulations were compared against flight test data, and simulator trials were carried out in the ONERA research simulator in order to evaluate the representativeness of the VRS models thanks to piloted simulations. The objective was to highlight potential shortcomings of the VRS models and thus the reservations to be taken into account when the vortex phenomenon and recovery techniques are evaluated through simulations, whether in delayed or in real time on simulators. Not expected at the beginning of the study, discrepancies in helicopter responses between simulation and flight data were noticed, and outlined flight mechanics deficiencies.

It was thus demonstrated that:

- The off-line simulation tool developed at ONERA and dedicated control strategies give the possibility to reproduce many different VRS test cases.
- When following flight data or in the framework of parametric studies, some influencing parameters and tendencies are well captured, such as the effect on height loss of delayed collective increase or pitch and roll angle maximum values.
- The vertical speed response was generally not representative of the flights, especially when using the OA VRS model. That’s true in terms of maximum descent rates reached after a collective pitch decrease, but also after a collective pitch increase in fully developed VRS.
- When using the ATR VRS model, the collective pitch increases are much more representative in fully developed VRS. On the contrary, pitch and roll artificial oscillations are not realistic, being too strong and too periodic. This prevented to assess this model with the Vuichard technique in the ONERA simulator. The cyclic efficiency coefficient proposed by this model has to be carefully set, to properly represent the power control reduction that can be experienced in flight.
- Simulator trials remain mandatory to correctly evaluate helicopter model behaviour and recovery techniques representativeness. In this study, these trials offered the possibility to evaluate both helicopter and VRS models with a pilot.
- It was thus confirmed that the cross-couplings and parasitic effects are neglected by the simulation, and more specifically on the Dauphin helicopter, equipped with a Fenestron and large rear aerodynamic elements.
- In addition, the absence of engine model and thus the lack of engine limits (Torque, NG) highly reduced the pilot workload during simulator trials compared to real flights. But this parameter has a great effect and it was demonstrated in flight that a higher workload tends to lower the recovery efficiency.

Following this study, dedicated improvements as well as suggestions for future researches have been proposed.

Recommendations have been issued on the use of simulation models to study the vortex phenomenon and/or to evaluate the recovery techniques.

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9. REFERENCES

1. " A Comparison of Traditional And Vuichard Vortex Ring State Recovery Techniques Using On-Line Simulation", E. Sotiropoulos-Georgiopoulos, A. Payan, C. Johnson, D. Mavris, Vertical Flight Society's 79th Annual Forum & Technology Display, West Palm Beach, FL, USA, May 16–18, 2023.
2. "Scenario-Based Helicopter Flight Simulation of Accident-Prone Vortex Ring State (VRS) Encounters", E. Sotiropoulos-Georgiopoulos, A. Payan, C. Johnson, D. Mavris, Vertical Flight Society's 80th Annual Forum & Technology Display, Montréal, Québec, Canada, May 7–9, 2024.
3. "Helicopter flight tests in steep descent: Vortex-Ring-State analysis and induced velocity models improvement", Jimenez, J., Taghizad, A., Arnaud, A., CEAS Aerospace Aerodynamics Research Conference, 2002.
4. "Experimental and theoretical investigations to develop a model of rotor aerodynamics adapted to steep descents". Taghizad, A., Jimenez, J., Binet, L., Heuzé, D., 58th Annual Forum of the American Helicopter Society, 2002.
5. "Helicopter Flight Dynamics - The Theory and Application of Flying Qualities and Simulation Modelling", Padfiel, G.
6. "A Qualitative Analysis of Vortex Ring State Using a Fully Time Marching Unsteady Wake Model", J. Bailly, ERF 36th European Rotorcraft Forum, 2010
7. "Investigating the Physics of Rotor Vortex Ring State using the Vorticity Transport Model", Ahlin, G.A., Brown, R.E., 31st European Rotorcraft Forum, Florence, Italy, Sept. 13-15, 2005.
8. "Predicting the Onset of Wake Breakdown for Rotors in Descending Flight", Newman, S., Brown, R., Perry, J., Lewis, S., Orchard, M., Modha, A., Journal of the American Helicopter Society, Vol. 48 (1), Jan. 2003.
9. "Prediction of Vortex Ring State Boundary of a Helicopter in Descending Flight by Simulation", P.M. Basset, Kolb (ONERA), Chang Chen, J. V. R. Prasad (Georgia Institute of Technology), Journal of the American Helicopter Society
10. "Investigations of the vortex ring state on a helicopter main rotor based on computational methodology using URANS solver", Stalewski, W., Surmacz, K., Lukasiewicz Research Network - Institute of Aviation Al. Krakowska 110/114, 02-256 Warszawa, Poland
11. D-1.1 VRS Knowledge Report – ttps://www.easa.europa.eu/en/research-projects/vrs-helicopter-vortex-ring-state-experimental-research