

ACTIVE SIDESTICKS USED FOR VORTEX RING STATE AVOIDANCE

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Abstract

A tactile cueing function using active sidesticks for Vortex Ring State (VRS) avoidance has been developed and was tested in DLRs ground simulator. The function uses a VRS prediction model developed by the ONERA, capable of predicting the actual closeness to the VRS onset during flight. The tactile cueing function was tested using 3 different tasks in a simulator. Workload ratings were performed and showed clear reductions with the cueing function and the pilots commented positively on the function. The cueing function is prepared for upcoming flight testing on the DLR Flying Helicopter Simulator (FHS). As preparations for flight tests, the influence of using real sensor data is analyzed.

List of abbreviations

ADS-33E	Aerodynamical Design Standard for military rotorcraft handling qualities
AGL	Altitude Above Ground Level
DLR	Deutsches Zentrum für Luft- und Raumfahrt / German Aerospace Center
FHS	Flying Helicopter Simulator
HQ	Handling Qualities
IAS	True Airspeed
MFD	Multi Function Display.
NASA-TLX	NASA Task Load Index.
ONERA	Office National d' Études et de Recherches Aérospatiales / French Aerospace Center
SAS	Stability Augmentation System
TAS	True Airspeed
VRS	Vortex Ring State

List of symbols

δ_{col}	Collective deflection [0-100%]
δ_{sop}	Sofstop onset point, measured in the same range as δ_{col}
ϵ	Number denoting the closeness to the vortex ring state.
F_z	Rotor lift [N]
g	Acceleration due to gravity. 9.82 [m/s ²]
$k_\epsilon, k_{az}, k_{bias}$	Constants
m	Mass of helicopter
ρ	Air density [kg/m ³]
R	Rotor radius, 5.1 [m]
τ	Time constant [s]
v_h, v_z	Horizontal and vertical airspeed. [m/s]
v_i	Mean induced velocity through the rotor. [m/s]
v_{i0}	Mean induced velocity through the rotor in hover. [m/s]

1 INTRODUCTION

Over the years, aviation safety standards have steadily improved. This is due to a tradition of safety awareness, high standards, and scrutiny of accidents. In the world of rotorcraft, the overall safety record is not quite as good as that of fixed wing aviation [1]. Studies on rotorcraft safety repeatedly point to the fundamental problem of pilot workload saturation. The helicopter pilot often finds himself in a situation where too many things simultaneously require his attention. Even if the next event is of a dangerous nature, he may not be able to cope up efficiently to all demands and may neglect to act upon certain events. If this happens in the wrong moment, the consequences can be catastrophic. One such situation is the vortex ring state (VRS) which

happens when a helicopter descends too fast at low forward airspeed. This leads to a recirculation through the rotor, which causes loss of thrust and leads to even higher rates of descent and poor controllability. Although helicopter pilots are trained to avoid the VRS, accidents are happening [2]. According to this source, the period from 1982 to 1997 saw at least 32 helicopter accidents due to VRS. Most of the accidents occurred at altitudes below 200 feet and at low forward speed. It was seen that, in many cases, the pilot did not recognize the situation as VRS and made matters worse by pulling up on the collective stick, thereby increasing the rate of descent further. This is the crux of the VRS: it leads to a rapid loss of altitude which, if flying low, prevents the pilot from successfully initiating countermeasures. Therefore, the best way to hand the VRS is

by avoiding it. This paper presents a method, which does this by cueing the pilot on the collective stick and it has shown easy and intuitive to use.



Figure 1: The Flying Helicopter Simulator

At the German Aerospace Center (DLR) and at the French Aerospace Laboratory (ONERA), much attention has been given to the subject of flight safety. The DLR performs flights with its Flying Helicopter Simulator (FHS) in the fields of tactile cueing, envelope protection, and handling qualities. For this it uses the FHS' fly-by-wire/fly-by-light control system which is capable of testing experimental algorithms. Equipped with two active sidesticks, the FHS is capable of testing active tactile cueing functions, which is a modern technology that is starting to show substantial advantages over other cueing functions [3]. This advantage is based upon the fact that pilots tend to block out aural and visual warnings when operating at high levels of workload. Use of the tactile information provides the pilot with useful cues directly at the interface between man and machine. This increases the chance that the cues are perceived and used.

Many subjects regarding flight safety have been investigated by the ONERA, among which the Vortex Ring State is a particularly dangerous one. The ONERA has conducted tests flying into the VRS and developed a modified Wolkowitch model [4], capable of calculating the actual closeness to the VRS based on measured data [5]. The DLR and ONERA have started an activity to develop a tactile cueing system for VRS avoidance. This is the subject of this paper which is divided into a number of parts:

- Present the developed tactile cueing function and provide an insight into how it works.
- Present results of simulator tests and discuss the selection of test maneuvers.
- Present the results from preparing the cueing function for testing on the FHS.

2 DESCRIPTION OF THE CUEING SYSTEM

For the development of the cueing system, a number of targets were seen: 1) Provide the pilot with information of closeness to the VRS. 2) Provide this information with minimal additional workload and maximum clarity. 3) Let the function work in a way that helps the pilot avoid the VRS without impairing his control authority. As to estimating the closeness to the VRS, the ONERA method is well established and experimentally verified. In delivering cues to the pilot with high clarity and low additional workload, simulator studies have shown [3] that tactile cueing appears the best suited method at the time. As to not impairing the control authority of the pilot, the cues were implemented using softstops, which allow the pilot to override at any time.

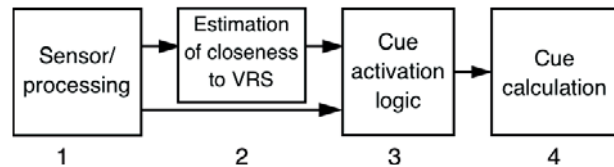


Figure 2: 4 steps of the cue generation process

When the VRS-avoidance function activates, the pilot senses that the forces on the sticks are different from the normal forces. Tactile cues appear as additional forces like soft- or hardstops, detents, breakouts etc. The computer, in preparing these, performs a number of steps as shown in figure 2: 1) Collect sensor data and process this for further use. 2) Estimate closeness to the VRS. 3) Depending on various sensor signals and closeness to the VRS, decide of if and what tactile cues should be activated to guide the pilot in avoiding the VRS. 4) Calculate the describing parameters for the tactile cues and send these to the active sidesticks. This approach is inspired by the ideas outlined in [6].

Since each of these steps plays an important role, the description in this paper of the tactile cueing system follows these steps:

2.1 Estimating closeness to the VRS

The cueing system takes as input a number denoting the closeness to the VRS. This number is called ϵ and it is based on a theory developed by the ONERA as described in [5] and [7]. ϵ is calculated by the semi-empirical formula:

$$(1) \quad \epsilon = \sqrt{\left(\frac{v_h}{k \cdot v_{i0}}\right)^2 + \left(\frac{v_z}{v_{i0}} + \frac{v_i}{2 \cdot v_{i0}}\right)^2}$$

v_h is the horizontal airspeed, v_z the rate of descent, v_{i0} the mean induced velocity in hover. v_i is the mean induced velocity through the rotor. v_i is not available as sensor data and so a theory based approach is used. It follows a two-step approach where the induced velocity in hover (eq. 2) is calculated using momentum theory and modified depending on flight state (eq. 3) [8].

$$(2) \quad v_{i0} = \sqrt{\frac{F_z}{2 \cdot \rho \cdot R^2 \cdot \pi}}$$

$$(3) \quad v_i = f(v_h, v_z, v_{i0})$$

F_z is the lifting force from the rotor. The parameter k in equation 1 has been fitted using flight data of real VRS encounters. Using a value of $k = 4$, and with (m, ρ, R, g) kept constant, ϵ forms a surface over the parameters (v_h, v_z) with a minimum inside the VRS-region [5] [8]. Moving away from the VRS-region leads to a monotonously increasing value. A value of $\epsilon = 0.25$ marks the experimentally verified limit for the VRS-region and higher values can be considered safe. This is shown in figure 3 where the value of ϵ is plotted for different rates of descent and forward speeds for a generic rotor with a diameter like that of the FHS and with a mass of 2500 kg and $\rho = 1.225 \text{ kg/m}^3$.

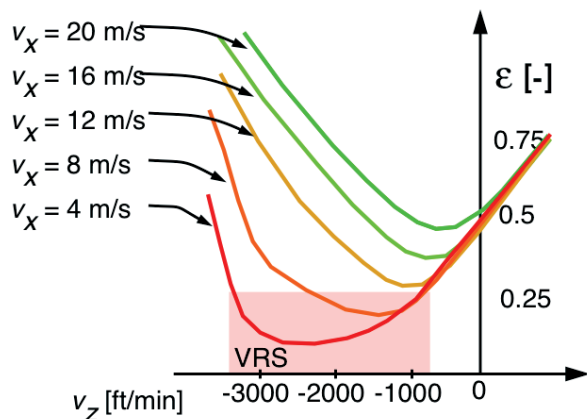


Figure 3: ϵ values in relation to airspeed

The value of ϵ is seen to drop while the sink rate increases. A value below $\epsilon = 0.25$ indicates a fully developed VRS. Higher and safer values are achieved by accelerating forward towards higher values of v_h or by reducing the rate of descent. Towards very high sink rates, the flow field around the rotor is once again in well defined region known as the windmill or autorotation state. There the danger of VRS disappears and the value of ϵ increases accordingly. The almost linear slope of ϵ in the region of moderate rates of descent makes it well suited for use directly in a control loop. Since the calculation of ϵ takes into account the air density and the mass of the helicopter, it gives a real time estimate of envelope limits which is more realistic than the rules of thumb approach employed by pilots.

This is shown in figure 4 where the estimated boundary of the VRS region is shown for varying values of m . The figure shows the boundary of the region where $\epsilon < 0.25$. It is evident that the boundary of the VRS-region changes significantly depending on gross weight of the helicopter. The corresponding observation regarding flight safety is that a pilot using fixed limits for the flight envelope may at times not be using the helicopters full potential.

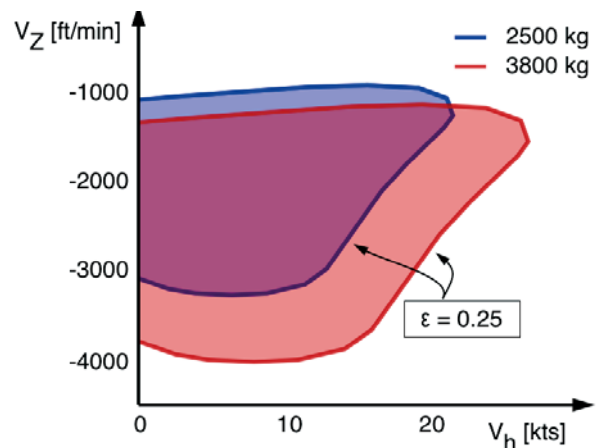


Figure 4: Estimated boundaries of VRS-region for the FHS for different masses

2.2 Cue activation logic

Having calculated ϵ , the next step for the cueing system to decide is if cueing should be activated at that particular time. This task is handled by the cue activation logic. At an early stage in the development of the cueing system, cues for the collective as well as the cyclic stick had been expected necessary and were developed. Two different approaches were developed and tested. The first was a velocity based logic, using a division of the flight envelope into fixed regions defined by velocities. A second and more adaptive approach was to base the cueing logic on ϵ alone.

2.2.1 Velocity based logic

The first cueing logic was based on dividing the flight envelope into regions depending on v_h and v_z . The division was based on preceding pilot interviews, questioning them in what situation different actions were required. The feedback can be summarized into a few simple rules:

- If flying slow, don't sink too fast
- If flying fast and sinking very fast, don't reduce forward speed
- If in a VRS, escape by increasing forward speed

These rules were implemented in a cue activation logic as shown in figure 5 which shows the cueing scheme around the VRS region bounded by the line at $\epsilon = 0.25$. Further out, a second line at $\epsilon = 0.35$ indicates a safety zone around the VRS where the cueing activates.

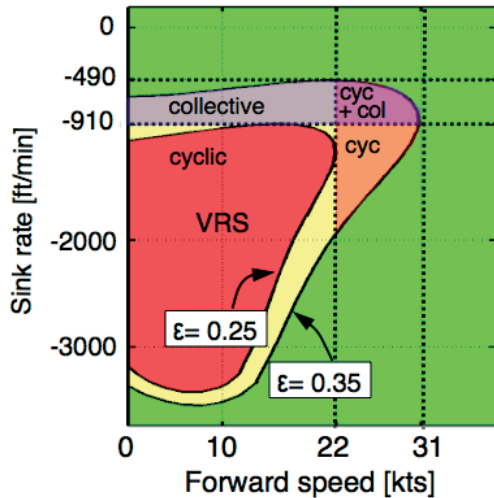


Figure 5: Velocity based cueing logic

By testing this logic in simulator trials, it was found that pilots preferred having only cues on the collective stick, meaning that the cueing logic could be reduced considerably (for further details, the reader is referred to [8]). Furthermore, it was recognized that using fixed limits for v_h and v_z would not utilize the full potential available with the real time calculated ϵ .

2.2.2 ϵ based logic

Contrary to the fixed limits of the velocity based cueing logic, an ϵ based cueing logic has the advantage that it fits to the actual situation. When the boundaries of the VRS-domain shift through changing air density or mass as shown in figure 4, the limits for activation of the tactile cueing are changed accordingly. With tests having shown that the pilots preferred a collective cueing only [8], the resulting cueing logic could be made very simple:

Logic	condition	meaning
IF	$\epsilon < \epsilon_{limit}$	Helicopter is in region with high risk of VRS
AND	$\dot{\epsilon} < 0$	and it is getting worse
THEN	cue ON	Activate collective cue
ELSE	cue OFF	Deactivate collective cue

This logic bases its activation on the closeness to the VRS domain. For tests in the simulator, it also had a feature that it disabled when the pilot was moving away from the VRS domain. Tests indicated that this logic was based on the right idea, but that it resulted in the cueing being switched on and off too fast. To avoid this and give the pilot an impression of a more constant cueing, a "hold ON" function was implemented.

Later tests showed that even this cueing logic could be further simplified. As will be explained in the following, using a softstop as cue has the advantage that the pilot only feels the cue once he is really pressing against it. When not "on" the softstop, the softstop is not felt and as a result, needs not be deactivated. So for the upcoming flight tests, the cueing logic can be reduced to a Boolean "1", meaning: "always ON".

2.3 Tactile cue calculation

After the cue arbitration, the next step of the cueing chain is to generate the cues. The cueing algorithm was developed using the same procedure as had earlier been used for cueing on the right hand stick [9] which had been inspired by the methods developed in the HACT program [10], [11], [12].

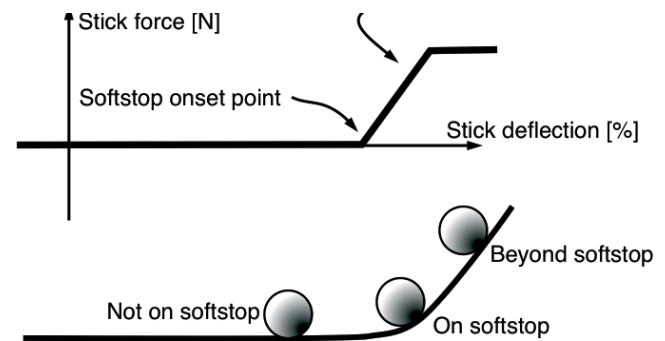


Figure 6: Stick pressed against softstop shown as a ball pressed up against an edge.

The collective cue works by preventing the pilot from commanding too high rates of descent. This is done by using a softstop opposing further downward movement on the collective stick as illustrated in figure 6. The ball rolling on the flat surface represents the collective stick in normal flight. Only forces being felt by the pilot are those from friction and mass. The softstop is felt as an edge against which the ball must be pressed. Using the cue as guide for the stick requires the pilot to maintain a light pressure, thereby pressing the "ball up on and against the edge". A consequence hereof is that the stick position is slightly biased compared to the softstop onset point. When the pilot loosens the force, the ball rolls to the bottom of the edge (softstop onset point) where the softstop is no longer felt. The position of the softstop is calculated so that, by pushing against it, the pilot attains the targeted rate of descent. Simple PD feedback control loops calculate the position of the softstop based on collective position δ_{col} , vertical acceleration a_z , vertical speed v_z or ϵ and a bias k_{bias} as shown in figure 7. It features two modes where either v_z (eq. 4) or ϵ (eq. 5) is limited. Both can be used separately or

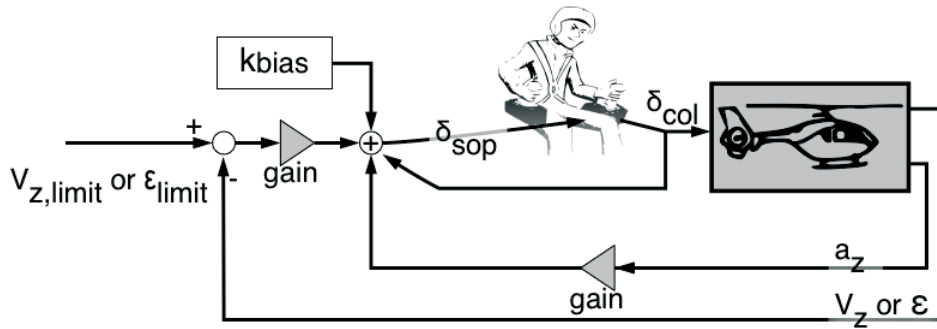


Figure 7: Control loop for calculating collective softstop onset point

simultaneously depending on the task.

$$(4) \quad \delta_{sop} = \delta_{col} + k_{vz} \cdot (v_{z,limit} - v_z) \dots \\ + k_{az} \cdot a_z + k_{bias}$$

or

$$(5) \quad \delta_{sop} = \delta_{col} + k_{\epsilon} \cdot (v_{\epsilon,limit} - v_{\epsilon}) \dots \\ + k_{az} \cdot a_z + k_{bias}$$

In figure 8, a test run in the simulator is shown. The pilot flies a vertical descent guided by a softstop on the collective stick, helping him maintain a sink rate of 400 ft/min.

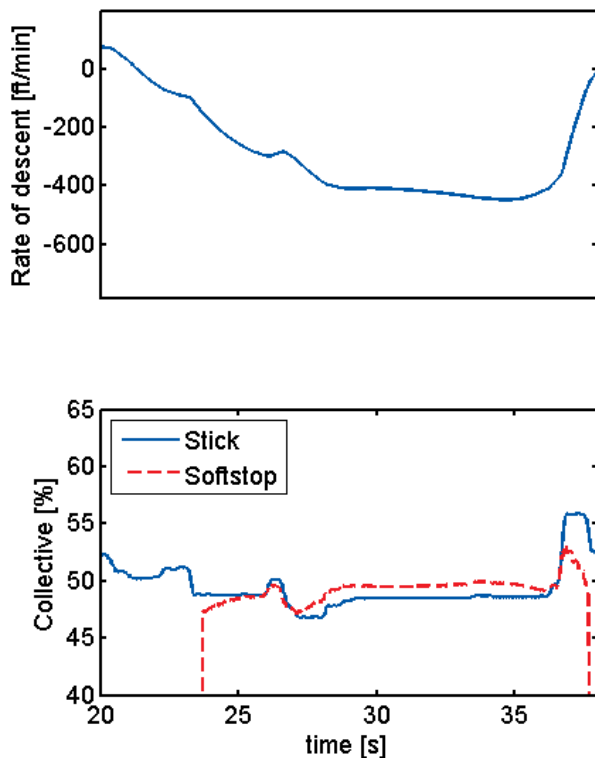


Figure 8: A vertical descent guided by a softstop on the collective stick

The upper plot shows the rate of descent and the lower plot shows the position of the collective stick and of

the softstop. At the beginning of the maneuver, the descent is initiated by lowering the collective stick. At $t \approx 23s$, the cueing logic activates the collective cue in the form of a softstop which at $t \approx 25s$ is reached by the collective. The pilot can be seen to slightly overreact to the cue $t \approx 27s$ by pulling away on the collective. Later, as the pilots got more used to using the cues, such reactions disappeared and they learned to stay with a firm stick pressed against the softstop. Stopping the descent at $t \approx 37s$ is done by simply pulling up on the collective and establishing a hover. The cueing logic can be seen to disable the softstop at $t \approx 39s$. Throughout the descent, as the softstop guides the pilot, a bias of a few % above the stick position can be seen. This is related to the "ball pressed up against an edge"-effect mentioned earlier as is the source for the k_{bias} mentioned in equation 4 and 5.

3 SIMULATOR TESTING

A first step in assessing the cueing function was to test it thoroughly in the FHS system simulator. The objectives were:

- With the ϵ calculation as an essential cornerstone of the cueing system, it was important to ensure correct and predictable output in all applicable situations.
- Test and ensure stable, correct, and predictable handling of the complete cueing system both with v_z -limitation and ϵ -limitation
- Test the cueing function using different tasks reflecting aspects of real helicopter operation. Perform workload ratings to show if the cueing function can offload the pilot.
- If possible, perform the testing using tasks from the Aerodynamical Design Standard for military rotorcraft handling qualities (ADS-33E) [13]. The reason is that the tasks in the ADS-33E are well proven and used widely in the rotorcraft community, ensuring comparability to other works.

Since one aim of the tests was to show that the cueing function offloads the pilot in a workload intensive situation, workload ratings were chosen over Handling Qualities (HQ) ratings. The field of HQ has a legacy with a wide catalogue of tasks suited for testing different aspects of helicopter flying. But since these tasks are designed to stay within a safe flight envelope, new task elements going closer to safety limits had to be designed. Three task elements were tested:

- Decelerated approach
- Vertical repositioning
- Flight along a downhill slope

All three were designed to give the pilot incitement to descent as fast as possible without entering the VRS. The group of pilots consisted of two DLR test pilots (A & B) and an experienced German army pilot (C). The two DLR pilots were familiar with active sidesticks and the simulator. The army pilot required familiarization with the sidesticks. The NASA-TLX [14] workload rating scale was used and all pilots were familiar with the method. The NASA-TLX asks the pilot to rate the demand along different factors. Secondly, it asks the pilot to weigh these factors. These ratings are then combined to give an index representing the workload as well as a weighed distribution of the factors. Another workload index used, was to count the number of control inputs on the collective stick.

3.1 Decelerated approach

During a flight test with the Dauphin 6075 from the ONERA, an incident occurred [15]. The pilot was to follow a 9° glide slope and decelerate during this. The task had been designed to be safe with regard to VRS but a wind change had given a slight component of tailwind. This resulted in a slightly lower forward airspeed than expected by the pilot and combined with the high sink rate, this led to a VRS encounter as shown in figure 9.

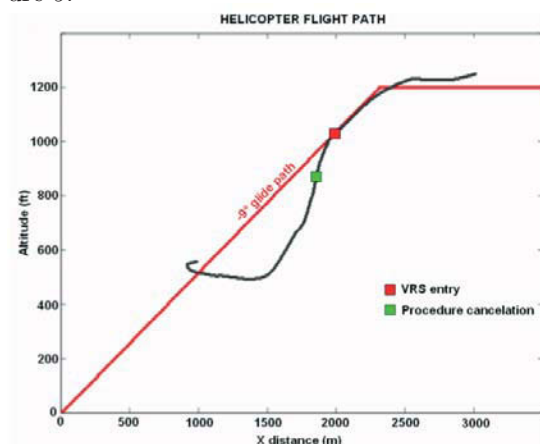


Figure 9: VRS encounter during steep approach. (Flight direction is right to left)

This incident was used as inspiration for the first task in the simulator testing. A ground device, indicating a 9° glide slope, as shown in figure 10, was designed and implemented in the simulator environment.



Figure 10: Visual guides for 9 decelerated approach

This scenario was tested but it was clear that in the simulator, this task was easy to perform and that VRS was easily avoided. Moreover, in real flight, contrary to the simulation, the pilot workload increases due to: 1) the influence of wind transients, 2) transient control modes of the auto-pilot of the Dauphin with changing airspeeds at around 40kts airspeed [15], 3) yaw instability near hover flight in case of tail wind, and 4) higher overall noise and vibration levels. The task was therefore not used for workload ratings but showed well suited for pilot familiarization. For the flight tests, on the other hand, a decelerated approach maneuver will very likely be part of the task catalogue.

3.2 Vertical remark

The 2nd task was taken from the ADS-33E design guide. It is the "vertical remark", also known as bob-up/bob-down, shown in figure 11. In its original form, it aims at testing the ability to "accomplish an aggressive vertical descent close to the ground". It also tests the "ability to combine vertical and lateral aggressive maneuvering as required to evade enemy fire if observed during a bob-up" [13]. In its application to testing the VRS-avoidance function in this paper, mainly the first of the objectives was tested.

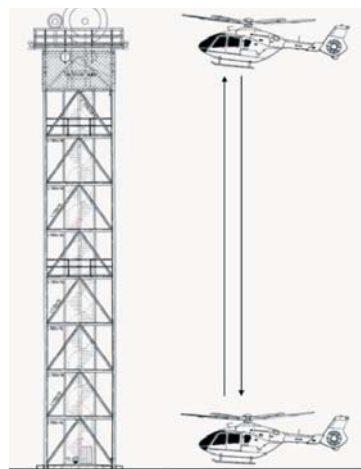


Figure 11: Vertical remark maneuver at the DLR telemetry tower

A telemetry tower on the grounds of the DLR, already available in the simulation environment, was used as maneuver reference. For the maneuver, pilots started from a stabilized low hover aside the telemetry tower. They then climbed to the top of the tower, stabilized a few seconds and descended to the original hover position. Contrary to the original maneuver as defined in ADS-33E, no requirements were made as to how well or how long the pilot has to hold the upper hover position since only maintaining safe rates of descent was of interest in terms of VRS. The pilots quickly familiarized with the cueing function. Using it as a guide for finding the targeted rate of descent was easy, as one pilot stated:

*You put down the stick [to the softstop].
You reach the max rate of descent, you go
down, and at the end of the maneuver, you
stop. That is it!*

It was found that the task duration was too short to give the pilot enough impressions to perform a workload rating. The task was therefore used for familiarization and for making observations and collecting pilot feedback. Some of these are:

- Despite the pilots feeling that the task was easy, measured data shows that without cueing, pilots did not achieve constant rates of descent during the maneuver. They had to repeatedly change focus between monitoring instruments and monitoring environment outside of cockpit.
- With cueing, a faster transition to the targeted rate of descent was repeatedly performed by all pilots. The cueing function also helped maintaining aggressive but steady rates of descent.
- As was shown in figure 8, with cueing, the pilots were able to remain closer to the limit for rate of descent over longer periods of time. They expressed that the workload in the collective axis was marginal to non-existent.
- Using softstops for the collective cue was appreciated since it allowed the pilots to push through the cue to reach a higher rate of descent if desired.
- With cueing, the number of collective inputs reduced by -20% up to -60% depending on pilot.

3.3 Downhill flight task

Another task requiring more piloting and with a longer duration allowing more time to collect impressions was defined. It was called the downhill flight: A hill of 130 m height over the surrounding area and covered with trees was built in the simulation environment as shown in figure 12.

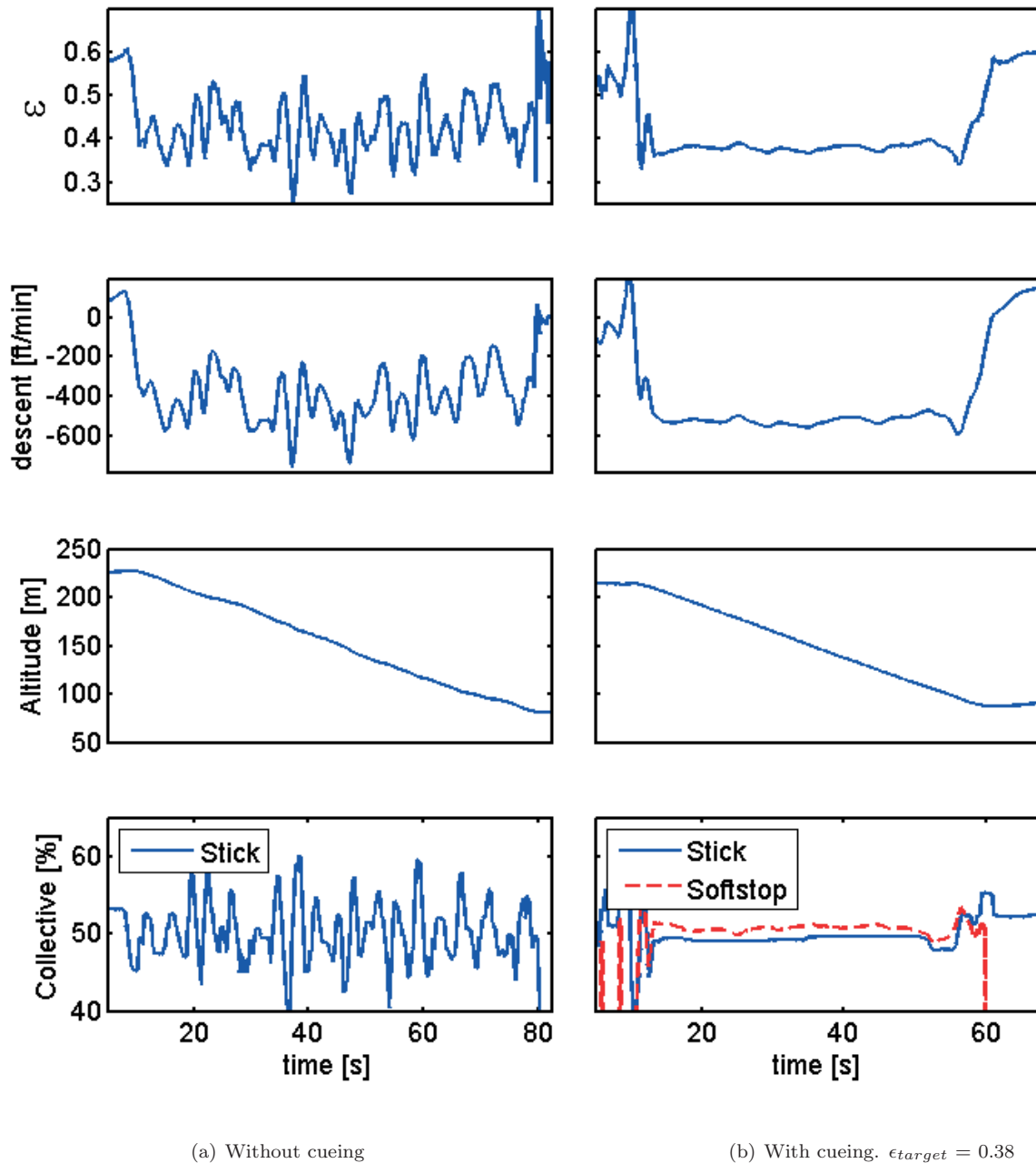


Figure 12: The hill seen in birds-eye perspective

Orange traffic cones were placed in an S-shape from the top to the landing point for the pilot to follow. A tailwind of 10 kts was added to increase the pilot workload during the maneuver. The main objectives were to do the maneuvers within a safe flight envelope like in a real helicopter, but also as fast as possible. Nevertheless, as in a simulator no risk of life is involved, and since the fixed base prevents the pilots from feeling acceleration and speed, it was very important to stress that the task was to be flown with the same caution as in a real helicopter. In this flight task, the pilots were asked to perform the following steps:

1. Start in a hover immediately above the ridgeline of the hill
2. Target and reach a rate of descent as high as you would feel comfortable with in real flight
3. Fly and remain below treetops
4. Follow s-shaped track marked by cones down along the slope
5. Stop to hover or land at the H at the foot of the hill

Overall, the task was described as difficult due to the high obstacle density and the required manoeuvring accuracy. This required the pilot to focus outside the cockpit, preventing him from monitoring the rate of descent on instruments. A contributing factor is also the simulator itself. A lack of accelerations and microtextures degrades the perception of motion for the pilot. They found the tactile cueing on the collective very helpful to maintain a safe descent rate without having to monitor instruments. Without cueing, the task was still flyable but pilots had to concentrate more on maintaining a safe rate of descent, which ultimately increased the workload and risk of accidents. A significantly higher workload compared with the vertical remark was noted and it was concluded that the maneuver was well suited for workload rating.



(a) Without cueing

(b) With cueing, $\epsilon_{target} = 0.38$

Figure 13: Comparison of the level of steadiness during the downhill maneuver without and with cueing on the collective stick

Recorded data from two test runs on the hill is shown in figure 13. It compares the maneuver without and with cueing on the collective stick. It should be noted that slightly different starting conditions appear in the two plots. This is not due to different test conditions but merely an effect of plotting recorded simulator flight data where the pilot is holding a hover prior to starting the task. The most important difference can be seen in the activity on the collective stick shown in the lowermost panels. Without cueing (left column), the pilot makes numerous corrections and is constantly controlling the helicopter. With cueing (right column), the activity is very much lower and

the stick is guided by the softstop. The pilot must no longer make continuous corrections and a much more steady behaviour is seen. The uppermost plots show the corresponding values of ϵ which, without cueing, can be seen fluctuate strongly and occasionally reach the predicted VRS limit of 0.25. With cueing, the ride is much smoother and ϵ stays firmly in a safe region and a much smoother ride with a reduced workload is attained. With the cueing helping in quickly attaining and maintaining the targeted rate of descent, an overall reduction in task duration can be seen: The test run without cueing takes roughly 70 s, whereas adding cueing, in this case, results in a duration closer to 50 s.

3.4 Workload of downhill maneuver

After each test run, the pilots rated their workload using the NASA-TLX rating method [14]. The pilots had the choice of activating a Stability Augmentation System (SAS) which performs a slight damping of pitch, roll, and yaw. The ratings are summarized in table 1 and the complete rating sheets can be seen in figure 20 at the end of the paper. A lower number denotes a reduced workload.

Configuration	Pilot		
	A	B	C
Cueing OFF, SAS OFF	0.9	0.84	-
Cueing OFF, SAS ON	-	-	0.99
Cueing ON, SAS OFF	0.52	0.8	-
Cueing ON, SAS ON	0.28	0.66	0.64

Table 1: Summarized workload ratings

The workload was reduced when the cueing system was used. Two pilots (A & C) experienced significant overall workload reductions with clear improvements in all rating dimension (see figure 20). For one pilot (B), the overall rating shows only a slight improvement. This pilot commented that the cueing reduced the workload on the collective but led to an increase of workload on the the cyclic stick in order to remain on the right glideslope. Furthermore, he noted that the cueing required a re-learning that may take time for experienced pilots. This behaviour was not observed with the other pilots.

Typically, the rating of the "physical demand", "temporal demand", and "effort" showed the biggest gains and "temporal demand" being rated very low. This has to do with the way how the cueing effectively shows a limit for the rate of descent. The pilots knew that descending faster was not an option and so, they had not to care about the duration of the maneuver.

By adding cueing, the number of collective inputs dropped -40% to -80% depending on the pilot.

4 PREPARING FLIGHT TESTS

Having developed the cueing function and tested it in the simulator, the next aim is the real flight test. Experience shows that going from simulator to flight requires some attention. A higher level of technical maturity must be reached to ensure incident free flight tests. Among the requirements are:

- Easy user interfacing for the crew: the less keys for the crew to press, the better they can focus on testing the cueing function.
- Flexibility: all parameter values used in the cue-

ing algorithm have been tested during simulator trials. Should parameter modifications show necessary during flight, these must be easily performed by the crew.

- Computational stable: it must be avoided that wrong data or data from un-initialized sensors can bring the experimental software to malfunction. This is done by employing robust algorithm structures.
- Compensation for systematic sensor errors: some sensors errors are deterministic, like for instance the airspeed sensor error at low airspeeds. These can be accounted for and workarounds can be made.

Preceding tests in the FHS system simulator had shown that the computation of ϵ was sensitive to non-physical input like data spikes or from un-initialized sensor signals. For this reason, the computation of ϵ was examined closely and brought up the three subjects: 1) computational stability, 2) nonlinearity of airspeed sensor at low airspeeds, and 3) input signal noise. Whereas the computational stability can be increased by applying robust algorithm structures, the nonlinearity in the airspeed sensor is based on physics and can not be processed to linearity in software. Last, the probability of noise requires filtering.

4.1 Airspeed sensor limitations

On the FHS, the airspeed is sensed using a pitot tube mounted on a nose boom which protrudes forward of the fuselage, thereby reducing the influence of the rotor downwash in most conditions. Still, at low speeds, the sensors on the nose boom become influenced by the downwash so that the airspeed sensor signal loses accuracy below 15 m/s.

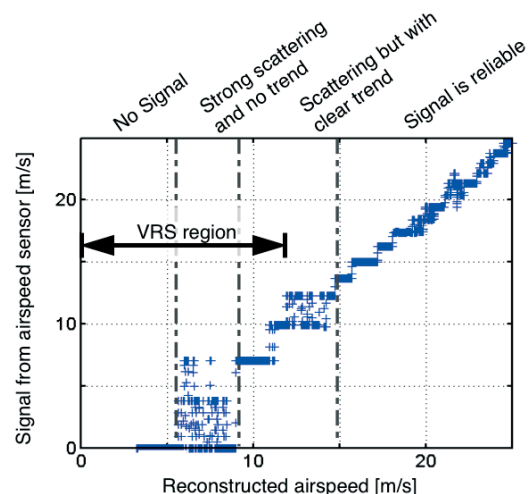


Figure 14: Signal from the airspeed sensor relative to reconstructed airspeed

In figure 14, a comparison of reconstructed airspeed and measured airspeed is shown. It can be seen that at zero airspeed, the airspeed sensor generates a zero output with no static noise. A nonzero signal is seen once the speed reaches ≈ 6 m/s. Up to ≈ 9 m/s a strong scattering is evident and the signal occasionally zeroes. Above this speed, a region follows where the signal is still scattered but where it shows a clear trend. This is also the speed range, below which the VRS becomes a problem. This overlap has the positive effect that airspeed measurements are available down to speeds, where the VRS starts playing a role. So, a simple, yet effective, solution has been made, in which the airspeed signal used for calculation of closeness to VRS is limited to values greater than 10 m/s. The effect of this is illustrated in figure 15.

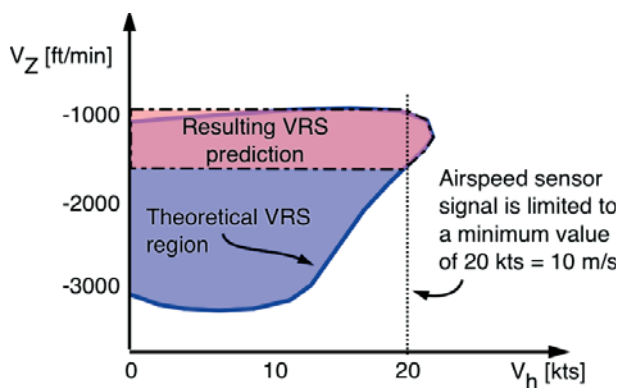


Figure 15: How capping the airspeed sensor signal influences the calculation of ϵ

By limiting the airspeed sensor signal to 10 m/s, the predicted boundary of the VRS is constant for airspeeds lower than this. The resulting error is seen to be limited. It actually results in a more conservative and safe estimate for the range of normal flight down to the onset of the VRS. This is also the range expected to have the greatest applicability to flight safety according to pilot interviews. For high rates of descent, the predicted boundary with limited airspeed signal is seen to differ strongly from the "real" prediction. A future solution to the problem of finding low airspeeds may come in the form of estimating low airspeeds based on control inputs and helicopter response. This has already been treated in [16] but the FHS has not yet such a functionality, so in order to facilitate flight tests, the practical approach presented here was chosen.

Obtaining the vertical airspeed v_z is even more problematic than v_h . One reason is that this parameter stays in a range well below ± 10 m/s where the dynamic pressure is very small. Another reason is the influence of the rotor downwash which dominates at low forward speeds. Since no easy method for estimating exists, a straightforward approach has been taken

where simply the vertical speed provided by the on-board inertial navigation system is used. This has a serious limitation in that it does not take the vertical wind speed into account. Any gust or thermal activity will offset the real value from the one used.

Regarding noise and other non-systematic errors: As figure 14 showed, once the airspeed is higher than 10 m/s, a signal with a relatively clear trend but with some scatter is seen. Viewed over time, this scatter takes the form of signal noise which should be filtered before being used for the computation of ϵ . This is done by using a combination of rate limitation and low pass filters. Figure 16 shows a plot of a spike with different filtering methods applied.

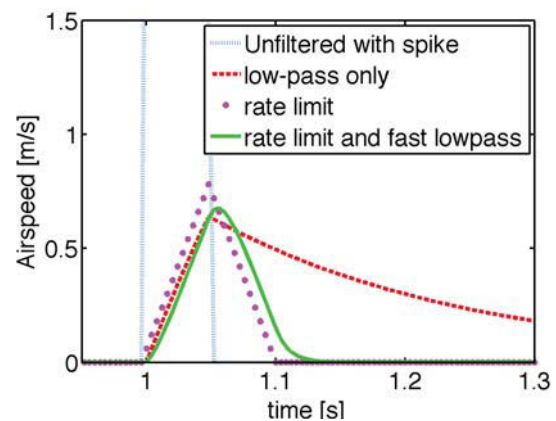


Figure 16: Suppressing a spike by using a combination of a rate limitation and low pass filter

A rectangular spike with a magnitude of 5 m/s with a duration of 50 ms is started at $t=1$ s and is shown as the finely dotted line. One option to suppress such spikes is by employing a low pass filter which smooths the signal. This is shown as the dashed red line. The filter needs to be quite slow in order to suppress the spike and a first order low pass with a $\tau = 200$ ms is used. Imposing a time delay of this magnitude can have negative consequences if the signal is used in a control loop. Furthermore, the filter needs time to return to the correct value. Another option is to utilize a rate limitation in front of the low pass shown by the magenta dots. The rate limitation is set high enough to allow any real physical signal to pass but still suppress an instantaneous change as characterized in a spike. The rate limitation in the example has a slew rate limit of 15 m/s² which is considered higher than any normal forward acceleration occurring on a helicopter. Combining the rate limitation with a low pass filter shows even better results. The time delay of the low pass filter can be chosen an order of magnitude smaller, still providing a substantial suppression of glitches as shown by the green line. It should be noted that the magnitude of the spike and the values in the filters are chosen for clarity of demonstration and they are an exaggeration.

generation and not representative of the signals that are normally acquired by the airspeed sensor on the FHS. Table 2 shows the value used for filtering the input signals to the calculation of ϵ and collective softstop.

Signal	Slew rate	Saturation	Cutoff freq.
v_h	$\pm 10 \text{ m/s}$	10 to 70 m/s	3 Hz
a_z	$\pm 10 \text{ m/s}^2$	0 to 20 m/s	3 Hz

Table 2: Filter settings for input signals to ϵ calculation

5 Choice of maneuvers

The simulator tests were performed under conditions that would be considered risky in real, like for instance the downhill maneuver. For the flight tests, such risks are not acceptable and other maneuvers must be used. This leads to the formulation of a 3 stage logical approach:

1. **With** the simulator tests showing the advantages of the cueing function while flying under critical conditions
2. **And** if flight tests can show that the cueing function provides the same level of protection and comparable handling to what was shown in the simulator
3. **Then** it may be assumed that the cueing function would help in a critical situation in real flight

The flight tests therefore take the subtle aim of proving the correct function of the cueing function. The objectives are:

- Show robustness of the cueing function in real flight with varying conditions such as gross weight, air density, rate of descent and forward airspeed while relying on available sensor data.
- Record data from the behaviour of the vertical motion of the FHS. This will be used to validate and fine tune the calculation of ϵ .
- Having shown that the function works reliably, fly maneuvers like decelerated steep approach where mental workload is high and perform workload ratings.

For reasons of safety, first tests of the cueing function will take place at safe altitude. Another reason for going high is that since no measurement of the vertical airspeed is available, the cueing function relies on rate of descent from the inertial navigation platform and assumes zero vertical wind speed. Such conditions are typically found in the "free atmosphere" above the convective boundary layer which on a typical day rises to between 1 and 2 km above ground level (AGL) [17] as shown in figure 17. Thermal activity does typically not

reach into the free atmosphere where also a relatively homogenous flow generates more constant wind speeds than at lower altitudes.

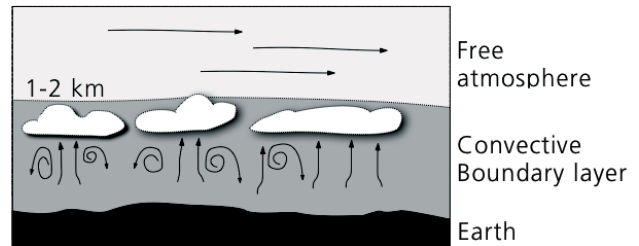


Figure 17: Division of lower atmosphere. Above the convective boundary layer, the wind is more steady and has less vertical component

The flight tests will consist of a number of steps, building experience with the different elements of the cueing system.

1. Fly without cueing at different rates of descent in the region near to the VRS and assess if the calculation of ϵ generates the expected output.
2. Test v_z -limit-cueing using safe rates of descent and at different forward speeds. Slowly increase rates of descent as handling with the cueing function gets familiar
3. Test ϵ -limit-cueing at different forward speeds and values of ϵ_{limit}
4. Once pilots gain confidence in the function, also maneuvers at low altitude such as vertical remask or steep approaches may be flown.

It should also be noted that another possibility for testing the ϵ based limitation has been conceived. By modifying the equations, an ϵ_{pseudo} can be calculated, which has comparable handling but assumes a VRS at higher and safer forward speeds as shown in figure 18. With this, it is possible to test the handling of the tactile cueing algorithm while flying at an airspeed which is safe with respect to the VRS.

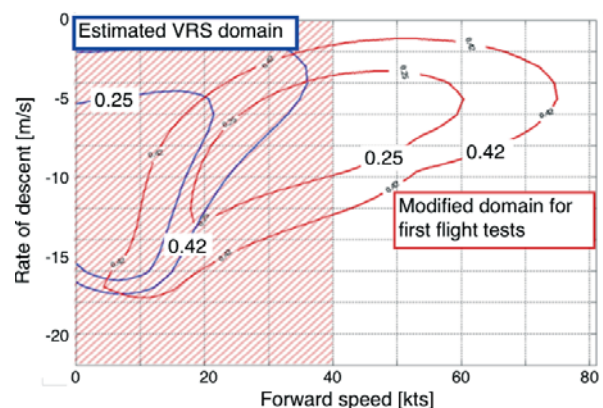


Figure 18: Using ϵ_{pseudo} instead of ϵ

5.1 Compensating for wind

One drawback of performing flight tests at altitude is that the ground references are not good enough for the pilot to perceive small changes in speed. The low forward speed prevents the sensors from measuring airspeeds and therefore the pilot is unable to monitor the airspeed. But in order to let the pilot control the test properly and for the test conditions to be well known, it is necessary to have information of the airspeed and give the pilot the possibility to monitor this. A more straight-forward approach has been developed. It uses the ground speed provided by the on-board inertial navigation platform coupled with wind speed estimates generated just before the actual maneuver. The concept is based on the addition of 2D velocity vectors:

$$(6) \quad v_{ground} = v_{wind} + v_{air}$$

v_{ground} is the speed relative to ground being continuously provided by the inertial navigation platform on the FHS. v_{wind} is the wind speed relative to ground which can be estimated by flying a wind estimation maneuver at forward speeds where the airspeed sensor gives reliable data. v_{air} is the airspeed of the helicopter relative to the air which is the parameter of importance for the VRS. Having an estimate for the wind and by assuming that it stays constant for the duration of the experiment, the airspeed of the helicopter can be estimated as

$$(7) \quad v_{air,estimate} = v_{ground} - v_{wind,estimate}$$

After flying a wind estimation maneuver, the pilot enters the wind direction and speed into the onboard computer. This manipulates the ground speed indicator, shown in figure 19, so that it now shows the estimated airspeed according to eq. 7. By reaching an indicated zero, the helicopter is in reality drifting with the estimated wind.

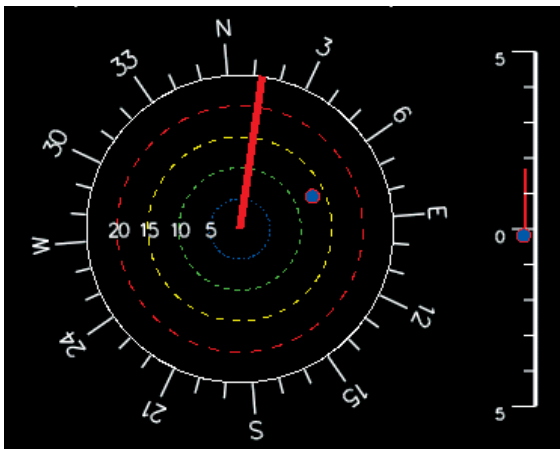


Figure 19: The hover display showing velocity vector as red line and estimated velocity in 5 seconds as blue circle.

The procedure for in-flight wind estimation has 4 steps:

1. Fly a circle at 40 kts IAS, finding the heading where the ground speed is at a minimum. The helicopter is now flying in a direct headwind. Refine by using the ground speed instrument shown in figure 19 to find the heading where helicopter has no lateral ground speed component while flying with minimal sideslip.
2. Maintain 30 kts IAS while heading into wind and record difference between ground speed and IAS.
3. Turn 180 and repeat step 2
4. Wind speed is assumed mean of recorded upwind and downwind wind speed.

6 NEXT STEPS

Having performed a ruggedizing of the cueing system software, the next step is to test it in flight onboard the FHS. Tests will be as described in the previous chapter and emphasis will be on showing a well-mannered cueing function that help the pilot avoid the VRS while not interfering with his choice of actions.

An interesting challenge is to optimize the airspeed estimation. A working solution that gives nearly correct results of the ϵ -calculation for the region of the VRS where most accidents happen has been developed. Precision is lacking at very high rates of descent as was shown in figure 15 and a more complete solution is wanted.

7 SUMMARY

A tactile cueing function for avoidance of the vortex ring state has been developed. It uses an active side-stick on the collective axis to signal and guide the pilot during phases where the vortex ring state is a threat.

The cueing function relies on a ONERA model that uses an adaptation of momentum theory to calculate the closeness to the VRS based on real time parameters.

Different combinations of cyclic and collective cues were tested and a configuration using only collective cueing was preferred by the pilots.

The function was tested using three different tasks in a ground based simulator of the DLR Flying Helicopter Simulator.

Safety improvements as well as workload reductions were recorded. The pilots quickly familiarized with the cueing function and were able to use it with very

little training. As a preparation for upcoming flight tests, the steps necessary to reach flight ready technological maturity have been analyzed. Filtering and shaping of sensor signals to compensate for noise and physical limitations has been designed and fitted based on analysis of flight data.

The cueing function allowed the pilots to rapidly reach a targeted sink rate and maintain this without exceeding safe limits. This observation was evident from recorded flight data as well as from verbal pilot statements.

It allowed a significant reduction in controller activity which was mirrored in improved workload ratings using the NASA-TLX method.

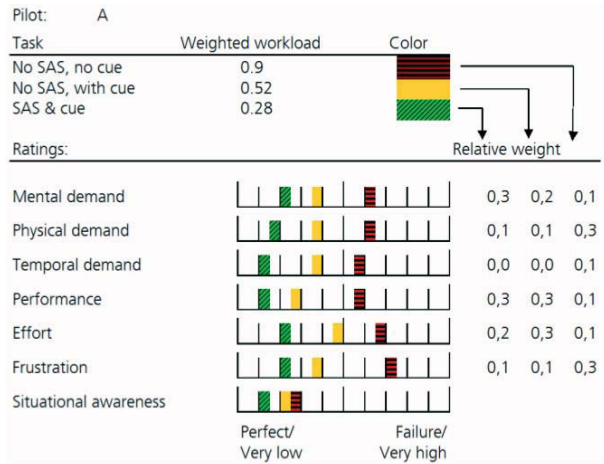
With it, a higher flight safety was achieved. The VRS domain was avoided throughout all maneuvers.

In many cases, tactile cueing gave rise to new piloting strategies. Pilots lowered the collective to the softstop and then only had to adjust the flight path downhill by adjusting the cyclic input. All pilots regarded this as easier than without cueing. One pilot noted that this transferred workload from the collective to the cyclic stick

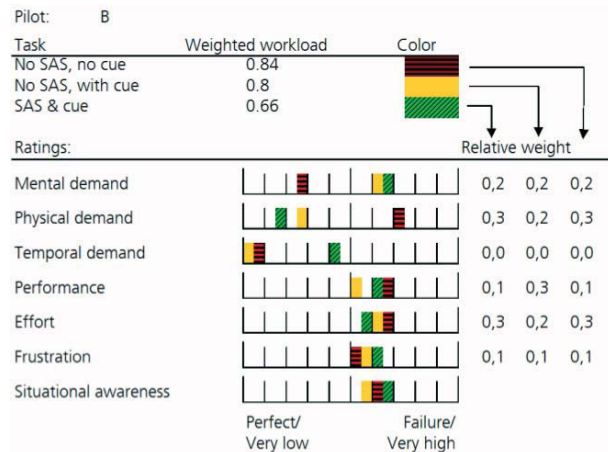
With the results from the tests suggesting that the cueing function allows the pilot to safely go closer to the VRS region, the question remains, how much closer is still safe? Flight tests will show.

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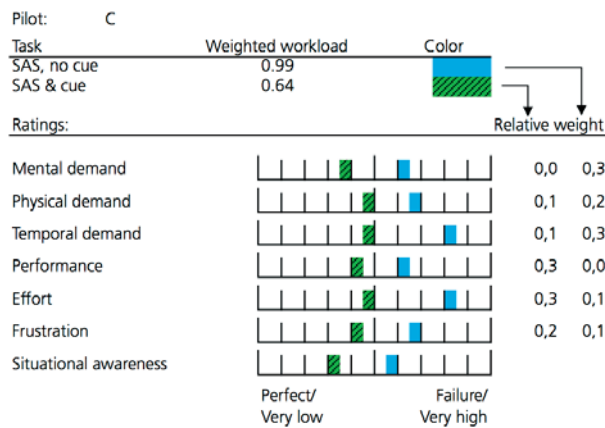
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(a) Downhill TLX pilot A



(b) Downhill TLX pilot B



(c) Downhill TLX pilot C

Figure 20: Complete TLX ratings from all participating pilots