

EVALUATION OF VORTEX RING STATE (VRS) ONSET AND ENTRY FIDELITY IN HELICOPTER FLIGHT SIMULATORS

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ABSTRACT

Helicopter flight simulators offer the potential to train pilots in recognizing, avoiding, and recovering from hazardous flight conditions such as Vortex Ring State (VRS). However, current FAA and EASA simulator qualification standards lack objective fidelity requirements for VRS onset representation, relying primarily on subjective assessments. Thus, this paper presents an objective evaluation method to assess how accurately different simulation models represent VRS onset. Using flight test data, from dedicated flight tests on a Robinson R66, and flight test results from the literature, fidelity criteria were established for key VRS onset aspects: collective trim position, vertical acceleration fluctuations, and sudden increases in descent rate. These criteria were used to evaluate three models: an H125 VR reduced-motion platform simulator, a FLIGHTLAB model with Peters-He inflow, and a more advanced but non-real-time FLIGHTLAB VVPM model. Results showed that while the VR simulator and VVPM model captured important VRS characteristics, they both had limitations. The Peters-He model failed to represent VRS onset cues. These findings highlight the need for improved simulation models to enhance VRS avoidance training effectiveness.

INTRODUCTION

On April 15th, 2020, a helicopter crashed in the Pyrenees. During flight instruction on a French Army's Cougar, the winds shifted unbeknownst to the crew, putting them in a tail-wind condition. While simulating an electric failure in hover, the helicopter entered Vortex Ring State (VRS), crashed, and caught fire, resulting in 2 fatalities, 3 serious injuries, and 2 light injuries. The pilots did not identify the phenomenon of VRS (Ref. 1). Indeed, VRS is one of the most commonly identified causes of Loss of Control in Flight accidents (Ref. 2). When a helicopter encounters VRS, the rotor is engulfed in a toroidal flow circulation pattern (Ref. 3), more commonly viewed as a donut shape around the rotor. This unusual flow circulation occurs when the descending rotor catches up with the disturbances in the wake, which then collapses from an ordered helical structure into an unsteady, chaotic re-circulating flow (Ref. 4). This phenomenon is dangerous for pilots since the emergence of such vortices on the rotor blades induces a rapid loss of the main rotor lifting ability (Ref. 5). For safety reasons and to limit the strain on the structure, the accident pilots had not received VRS flight training. The flight simulator used by pilots for training had a very

unrealistic model of VRS and did not allow for accurate VRS training either. Therefore, the pilots only received theoretical training on the VRS phenomenon; as the pilot had received a lecture on VRS the month preceding the accident. This theoretical training proved insufficient in preventing the accident, therefore, the accident investigators recommended the use of accurate VRS flight simulators for crew training.

Flight simulators could allow for training of pilots in recognizing, avoiding, and recovering from VRS. Indeed, in 2014, in response to the ongoing safety concerns within the helicopter industry due to accident rates, the NTSB issued a safety alert (Ref. 6) advocating the inclusion of simulator-based training for helicopter pilots. This safety alert underscored the NTSB's conviction that approved simulator training has the potential to improve pilots' proficiency in managing in-flight emergencies while minimizing maneuver errors. It contended that traditional flight training often falls short in replicating the element of surprise and intricate real-world complexity that pilots might encounter during an emergency. Along the same line, the USHST published a Helicopter-Safety Enhancement (H-SE), H-SE 81 (Ref. 7), focusing on simulators and outside-the-envelope flight conditions. The H-SE highlighted the risk of negative pilot training in helicopter simulators due to inaccurate flight dynamic models. The team provided recommendations for the development of improved physics-based models for various dangerous situations. Among the seven identified flight conditions and maneuvers that would benefit from model improvements, Vortex Ring State was singled out as the most critical.

Full Flight Simulators (FFS), recognized as the most complex and widespread of the qualified helicopter flight simulators, warrant a more thorough examination of the fidelity speci-

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fications for flight in VRS. These requirements are listed in the FAA Qualification Performance Standards for Helicopter Full Flight Simulators (Ref. 8) and in the EASA Qualification Specifications for Helicopter Flight Simulation Training Devices (Ref. 9). In these documents, it is apparent that the assessment of simulators' behavior in VRS is predominantly reliant upon subjective evaluations conducted by the qualifying authorities. Therefore, there are currently no objective, quantifiable requirements for helicopter flight simulators' performance and accuracy in VRS entry and recovery in the FAA and EASA qualification standards. The need for revisions of the simulators' qualification standards has been acknowledged in the USHST's H-SE 81 on helicopter flight simulation model fidelity improvements (Ref. 7), introduced previously. Indeed, one of the recommendations outlined by the team was to update FAA policy (FAA Orders), guidance (Advisory Circulars), and regulatory material (i.e., rule changes to 14 CFR Part 61) related to helicopter simulators.

STUDY OBJECTIVE

Starting in July 2023, the authors conducted a study in three flight simulators. This study aimed to develop a proof of concept for the implementation of scenario-based training, focusing on VRS-inducing situations, examining the actions that lead to VRS-related crashes, and laying out the pilot's decision-making process during the event (Ref. 10). The study highlighted that to detect VRS encounters in the simulators, pilots relied primarily on visual cues of descent rate increase at slow speeds: either from looking outside or at the vertical speed indicator. Some sensory and auditory cues such as increased vibrations, stick shake, and rotor noise were also reported. Finally, some pilots identified the VRS encounter by pulling the collective and noticing that it did not arrest the descent. Therefore, a correct representation of these VRS onset characteristics is essential to enable VRS avoidance training in flight simulators. However, the current simulator qualification standards discussed earlier do not provide specific requirements for the representation of these characteristics.

The work presented here thus aims to define and apply fidelity criteria for VRS onset and entry characteristics in helicopter flight simulation models. Three aspects of VRS onset and entry are investigated: the collective position in trimmed steep descent, the vibratory cues in trimmed steep descent, and the drop in descent rate during entry maneuvers.

SIMULATION MODELS CHOSEN FOR EVALUATION

Three models that represent different levels of modeling complexity, application context, and future potential are evaluated in this work.

First, a piloted flight simulator presented in more detail in the next section was used. It is an H125 VR reduced-motion platform simulator developed and commercialized by Loft Dynamics (Ref. 11). This training device is representative of the new generation of compact, commercially available, qualified

simulators. Its use in the study will help develop evaluation methods for proprietary products that must be treated as black boxes. Moreover, this simulator was used by the authors to develop accident prevention training; therefore, knowing its capabilities and limitations was necessary to ensure the effectiveness and realism of the training.

The second model evaluated was an in-house H125 FLIGHTLAB simulation model using the Peters-He dynamic inflow. While capable in quasi-steady descent and hover conditions, the Peters-He model may underrepresent the nonlinear wake interactions and recirculating flow typical of VRS, particularly due to its simplified dynamic inflow structure. This inflow model is, however, widely used in rotorcraft flight dynamics, and is representative of the type of inflow typically used as a basis for simulator models prior to tuning and empirical adjustments by simulator manufacturers (Ref. 12). We chose to model an H125 to match the Loft Dynamics flight simulator at our disposal.

The last model chosen for evaluation is an in-house H125 FLIGHTLAB simulation model with VVPM. VVPM is claimed to accurately represent the complex vortex ring structures and blade-wake interactions that characterize VRS (Ref. 13). Although not currently suitable for real-time applications, ongoing research aims to create linearized, real-time models based on VVPM (Ref. 14), (Ref. 15). Thus, evaluating a VVPM implementation in VRS could help determine its potential for future flight simulators.

With these choices of simulation models, this work aims to provide a comparison of how different modeling strategies handle the nonlinear and unsteady aerodynamic environment of VRS. Understanding this is essential to both validate current training technologies and inform the development of future real-time simulation models.

EXPERIMENTAL SET UP

R66 Test Helicopter

Flight tests were performed on a Robinson R66 helicopter provided, operated, and partially equipped by EIT avionics (Ref. 16). Details about the instrumentation of the helicopter are provided in (Ref. 17).

Flightlab Models

A helicopter model resembling the Airbus H125 was developed and validated in Flightlab. Two versions of the models are implemented, one with the Peters-He six-states inflow model and another with the more accurate Viscous Vortex Particle Method (VVPM). The Flightlab modeling serves to supplement the flight test results in the evaluation of the flight simulator as it enables the use of more accurate but non-realtime inflow models. The model's implementation and validation is presented in (Ref. 18).

Helicopter Flight Simulator

Simulator trials were conducted on an H125 simulator platform, installed at the FAA’s William J. Hughes Technical Center (WJHTC) in Atlantic City, NJ, and developed by Loft Dynamics (Ref. 11). It is a reduced motion platform with virtual reality and a fully functional cockpit of an Airbus H125. In March 2023, EASA issued FSTD special conditions (Ref. 19), which makes the simulator qualifiable as an FTD Level 3, and in July 2024, the FAA qualified the H125 as a Level 5 Flight Training Device (FTD).

EXPERIMENTAL RESULTS: COLLECTIVE TRIM IN STEEP DESCENT

First, a flight test on an instrumented Robinson R66 was performed. It aimed to provide flight test data on the collective trim input as a function of rate of descent and forward flight speed. Assuming the data obtained provides exploitable results, the data can be used along with results from the literature to develop a fidelity criterion for the simulator evaluation.

R66 Flight Test

Experimental Method The following process details the initial flight test plan designed, and tested in the helicopter.

1. Fly to the test area
2. Wind observation in the test area, determine wind speed and direction
3. Determine headwind heading, all test points are then flown at that heading
4. Starting at a high altitude in a hover, stabilize the helicopter at a constant descent rate with 100 ft/min increments. Find the rate of descent (V_{zlim}) at which the descent becomes unstable (i.e. trimming becomes impossible), and note the corresponding manifold pressure
5. Repeat the descent three times at 0 knots and 10 knots of forward flight speed

Two main issues were encountered during this test. A first and well-known issue, is the airspeed indicator’s inability to precisely measure and display low airspeeds. Unfortunately, the aircraft was not equipped with additional instrumentation to display airspeed accurately at low speed (such as the one designed and used in the EASA/ONERA study (Ref. 20), or as is available in the flight simulator). Consequently, the pilot had to rely mostly on visual references to maintain the airspeed. Given the expected difficulty in holding a precise target speed under these conditions, multiple descents were flown, and the resulting data were analyzed to identify stable trimmed segments along with their corresponding airspeed and descent rate.

A second issue, is that the pilot was unable to maintain the steeper descent rate targets with no forward flight speed.

Therefore, changes to the descent procedures were made for vertical speeds below -500 ft/min. Instead of maintaining a hover and then slowly establishing the desired rate of descent, the pilot established the rate of descent with forward flight speed and then slowly decelerated to a hover.

Results From the flight test data, the trimmed segments are extracted. These are defined as segments for which the lateral speed, longitudinal speed, and descent rate, are maintained stable for at least 3 seconds.

Figure 1 shows a heatmap of the helicopter’s torque depending on non-dimensional vertical and horizontal speeds where blue denotes a low torque and red a high torque. It is worth mentioning that the effects of altitude and weight changes are neglected in this analysis. We observe that at shallow descent rates and low forward flight speeds, there is a clear decrease in the torque requirement with the increase in descent rate and airspeed. At a steeper descent rate, for μ_z between -0.6 and -0.8 and μ_x below 0.8, the torque requirement seems irregular since some high torque measurements are measured. However, these few anomalies are not sufficient to conclude on the helicopter’s behavior in this region, therefore we then look at other flight test results in the literature.

Literature Review Results from the EASA/ONERA flight test campaign on the Fennec (military variant of the H125) indicate that in shallow vertical descents up to approximately -500 ft/min, the relation between collective input and vertical speed curve is relatively monotonic, although there is a dispersion in the flight test data obtained. More precisely, there is a decrease in the required collective input with the increase in rate of descent; our R66 flight test results align with this trend. This behavior also reappears at descent rates exceeding -3000 ft/min. Conversely, between -1000 ft/min and -3000 ft/min, the collective input versus vertical speed relationship becomes non-monotonic; multiple, distinctly different descent rates can occur for the same collective input (Ref. 20). Mathematically, this implies that the function mapping collective input to descent rate is neither monotonic nor injective. From these observations, our first simulator fidelity evaluation criterion is defined as follows.

Fidelity Criterion Based on the observations above, the following fidelity criterion is defined: if the simulation accurately represents VRS onset and entry, then within the theoretical VRS onset boundary, the mapping from collective input to descent rate is non-monotonic and non-injective.

We now need methods to determine whether the flight simulator and flight simulation models investigated meet this criterion.

Flight Simulator Evaluation

Experimental Method In a trimmed descent, the collective position of a given vehicle depends on: vertical speed (V_z), airspeed (V_x), weight, altitude, and Center of Gravity (CG)

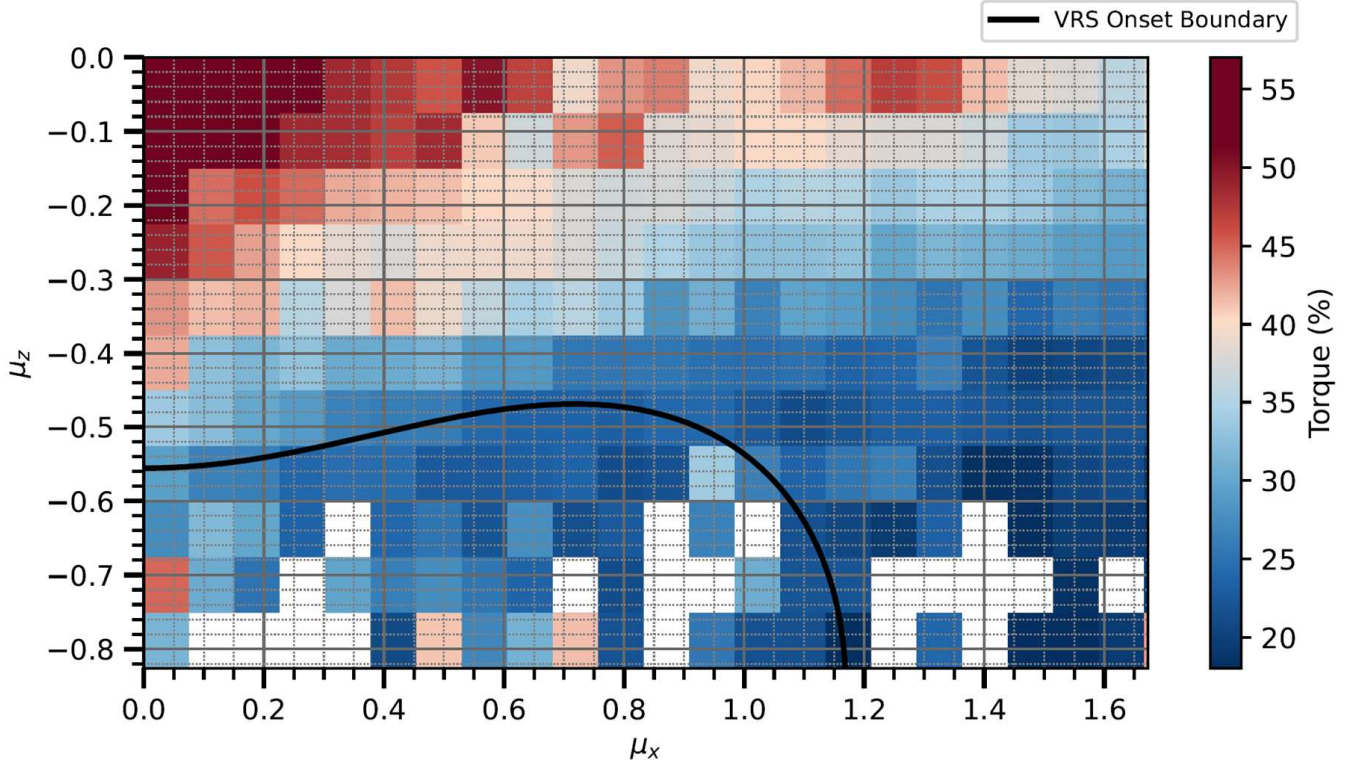


Figure 1. R66 torque in trimmed flight

Variable	Values
Helicopter Model	H125 Flight Simulator
Forward Flight speed	0 - 20 kts (1 knot-increment), 20-30 kts (5 kt-incr.), 50 kts
Weight	[Low, Medium, Max.]
Descent Rate (RoD)	Starting at 0 ft/min, 100 ft/min increments

Table 1. Collective Trim: Simulator Experiment Parameters

position. The effect of CG position and altitude changes are neglected in this study. Therefore, the goal of this experiment was to determine the collective trim position depending on descent rate, airspeed, and weight in the H125 flight simulator.

To collect the required measurements, the simulator flight assistance is enabled for the full duration of the simulations. This lets the simulator operator control the forward flight speed, lateral speed, vertical speed, and yaw rate from the operating station. That way, the trimmed conditions can be maintained more precisely than with a pilot.

The simulator is configured and operated as follows:

- **Configuration:** For each weight setting in 1, the weight is selected, and the fuel consumption simulation is disabled.
- **Start:** For each forward flight speed value, the simulation and data recording are started in a hover at 3000 ft AGL with the flight assistance enabled.

- **Descent:** The descent rate is increased, with 100 ft/min increments, maintaining each value for at least five seconds after it is reached.
- **End:** The simulation and recording are stopped either after the maximum vertical speed programmable in the flight assistance is reached (~1900 ft/min) or when the flight assistance can no longer maintain the target vertical speed.
- **Repetition:** For each combination of forward flight speed and weight, this stepped descent is performed twice in a row to verify the consistency of the results.

Results When processing the simulator data, the middle 3 seconds of each descent step are extracted, and the average collective position is calculated. Virtually no difference is observed between the two repetitions of each parameter set, thus proving the consistency of the measurements.

Figure 2 shows the evolution in the collective trim position with descent rate at various airspeeds at medium weight. We observe that below 1200 ft/min of descent rate at all forward flight speeds, the collective trim input decreases almost linearly with the increase in descent rate. This is also true at higher descent rates above 30 knots. Below 30 knots at steeper descent rates, the function from collective input to descent rate becomes non-monotonic, and, since it is continuous, it is non-injective. This behavior is more pronounced at the lowest forward flight speeds, below 10 knots, at some point in the descent, the collective input abruptly increases until maximum torque is reached. There, the flight assistance maintains the

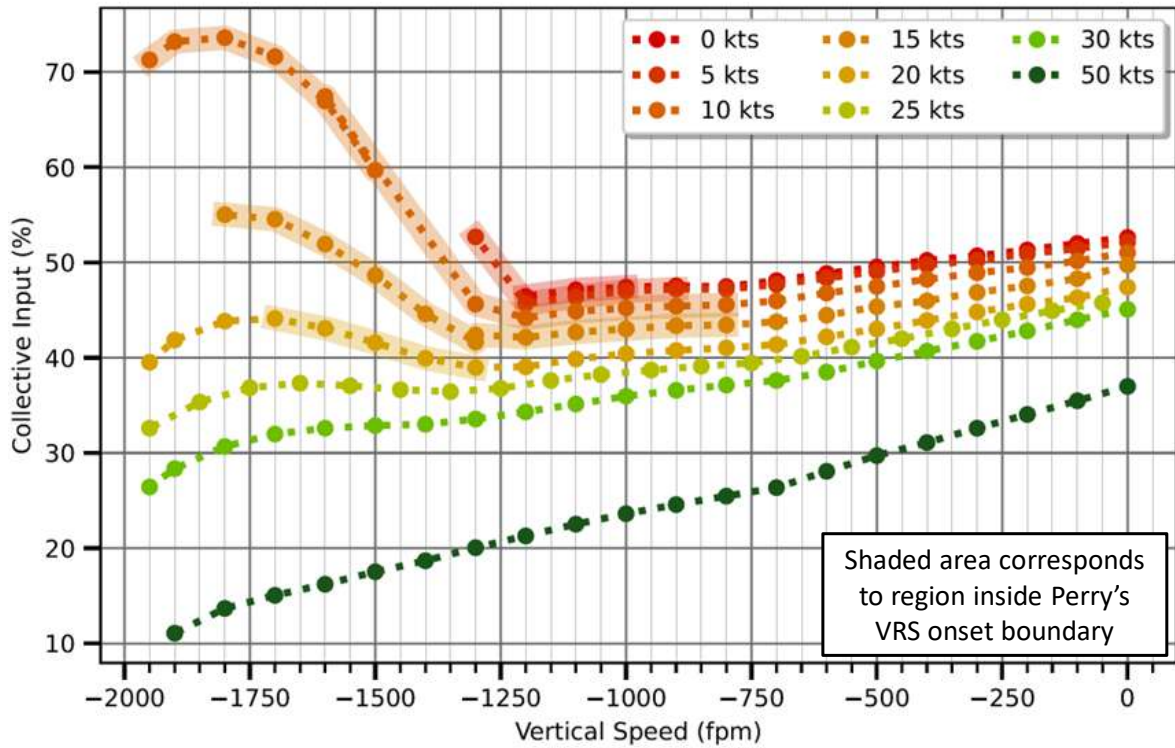


Figure 2. Collective trim position in descent in the H125 flight simulator at medium weight

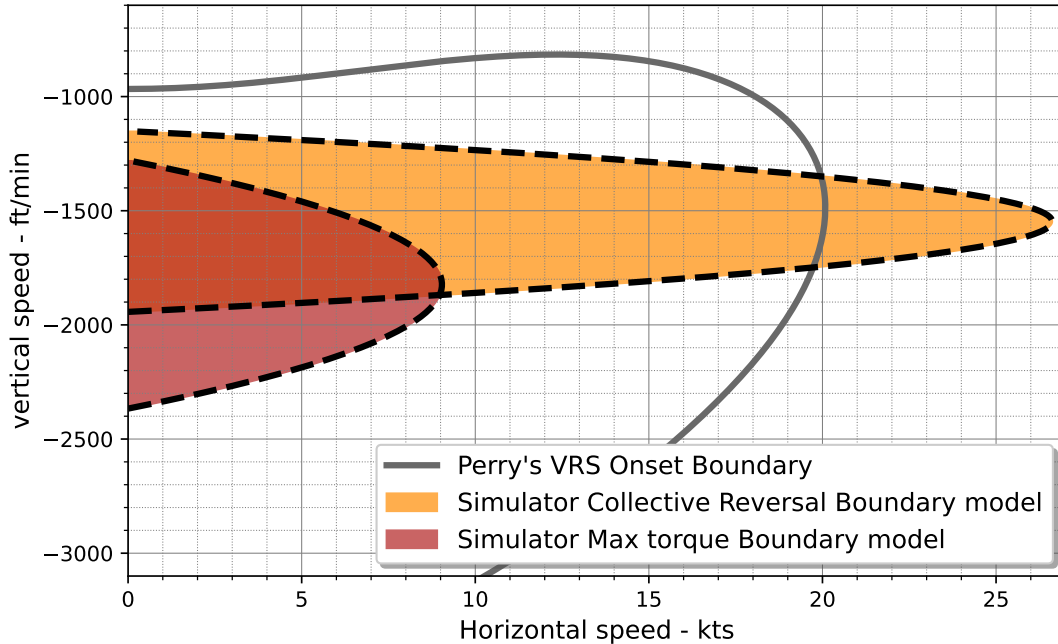


Figure 3. H125 flight simulator collective reversal region and max. torque region at medium weight

collective, and the simulator stabilizes at a much steeper rate of descent than requested. This is why the curves for 0 and 5 knots end at much shallower descent rates than the rest of the curves. To verify criterion 1.1, we need to determine whether this behavior coincides with VRS onset.

For each forward flight speed value at all three weights, the

descent rate corresponding to the first turning point is collected (where the collective starts increasing with the increase in descent rate), as well as the second turning point (where the collective starts decreasing again). Interpolating from these values, a parabolic curve outlining this collective reversal region can be traced, as shown in orange in Figure 3 for medium

Variable	Values
Forward Flight speed	0 kts - 25kts (1 kt-increment), 50 kts
Weight	Low - Medium - MTOW
Descent Rate	Starting at 0 ft/min to -2500 ft/min, 100 ft/min increment

Table 2. Parameters to model the collective trim position in steep descent in FLIGHTLAB

weight. Similarly, we can create a parabola to delineate the region where the simulator reaches maximum torque, as shown in red in the same figure. For comparison, Perry’s VRS onset boundary model was plotted (Ref. 21). It appears that both the collective reversal and the maximum torque regions are mostly contained within Perry’s VRS onset boundary. It is also worth noting that the upper limit of the collective reversal region is at steeper descent rates than the upper bound of Perry’s boundary.

Concerning the impact of the weight setting on the shape of the collective reversal region and of the maximum torque region: as weight increases, the collective reversal region shifts downward, while the maximum torque region shifts both downward and leftward. A similar trend is observed for Perry’s VRS onset boundary model, which also moves downward and to the left with increasing weight.

From these results, it appears that our fidelity criterion is validated in the simulator.

FLIGHTLAB VVPPM Model Evaluation

Experimental Method Similarly to the simulator experiment, the goal of this experiment was to determine the collective trim position depending on descent rate, airspeed, and weight with our H125 FLIGHTLAB VVPM model. To do so, for each combination of weight, forward flight speed, and descent rate values (as provided in Table 2), the model is trimmed and, if the trim function converges, the corresponding collective input position is recorded. Trimming the VVPM model in FLIGHTLAB involves several steps: first, setting the test conditions (weight, horizontal speed, and vertical speed); second, trimming the model without the VVPM wake model; third, initializing the VVPM rotor wake by running it for 50 rotor revolutions; and finally, trimming the model with the wake. This process takes around 10 minutes per case, or more if the trim function does not converge rapidly. The entire procedure was automated using iteration loops across all parameter combinations.

Results Following the same format as the simulator results, Figure 4 shows the evolution in the collective trim position with descent rate at various airspeeds at medium weight. Similarly to the flight simulator, we observe a region for which the collective trim input decreases almost linearly with the increase in descent rate. This is the case at low descent rates at all airspeeds, and at all descent rates at high airspeeds. We also observe a region, at steep descent rates, below 10 knots,

for which the collective trim input behavior is chaotic, clearly non-monotonic and non-injective. Between 10 and 20 knots, a collective reversal effect is also observed, however, it is less pronounced and occurs at much steeper descent rates. To verify criterion 1.1, we need to determine whether this behavior coincides with VRS onset.

For each forward flight speed value at all three weights, the descent rates corresponding to the first turning point (where the collective begins increasing with increasing descent rate) and the last turning point (where it resumes a consistent decrease) are collected. Unlike the simulator results, these points do not form a clear parabolic shape and are therefore plotted directly, along with the region they delimit, in Figure 5 for the medium weight case, alongside Perry’s VRS onset boundary. Two regions are defined, the lighter one corresponds to the highly non-linear behavior observed below 10 knots in Figure 4, the upper limit of this first region aligns with the upper limit of Perry’s boundary. The darker region corresponds to the smoother collective reversal observed above 10 knots. It begins at a much steeper descent rate, therefore, the upper limit of this region is significantly lower than that of Perry’s boundary.

From these results, it appears that our first fidelity criterion is validated below 10 knots for this model.

FLIGHTLAB Dynamic Inflow Model Evaluation

Experimental Method To evaluate our H125 FLIGHTLAB dynamic inflow model, the same method used for the VVPM model is applied. The computation time is much faster since the trimming process for each set of parameters does not require initializing the wake.

Results Figure 6 shows the evolution in the collective trim position with descent rate at various airspeeds at medium weight. At 0 knot there is a very slight collective reversal observed below -1000 ft/min. At all other flight speeds, the behavior is monotonic, almost linear.

From these results, our first fidelity criterion is not validated for this FLIGHTLAB model. This means that, without additional tuning or modification, this model, if implemented in a flight simulator, would result in negative training in steep descents.

Outcome

Our goal was to define and apply a method assessing the representation of collective trim input in steep descent for the flight simulation models evaluated. We achieved it by first designing a flight test plan to determine the variations in trimmed collective position in steep descent as a function of forward flight speed and descent rate. This plan was then tested in an instrumented helicopter; unfortunately, the results, when approaching VRS, were inconclusive. Therefore, the fidelity criterion for collective position in steep descent was instead derived from flight test results found in the literature.

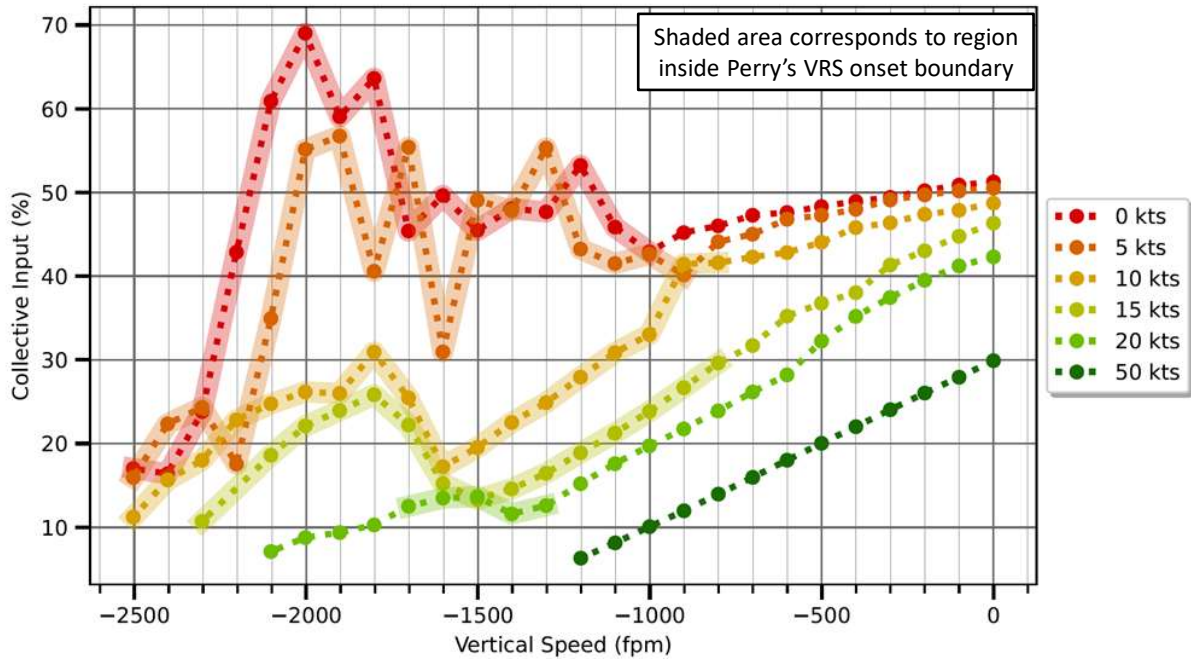


Figure 4. FLIGHTLAB Model with VVPM at medium weight - Collective input in trimmed descent

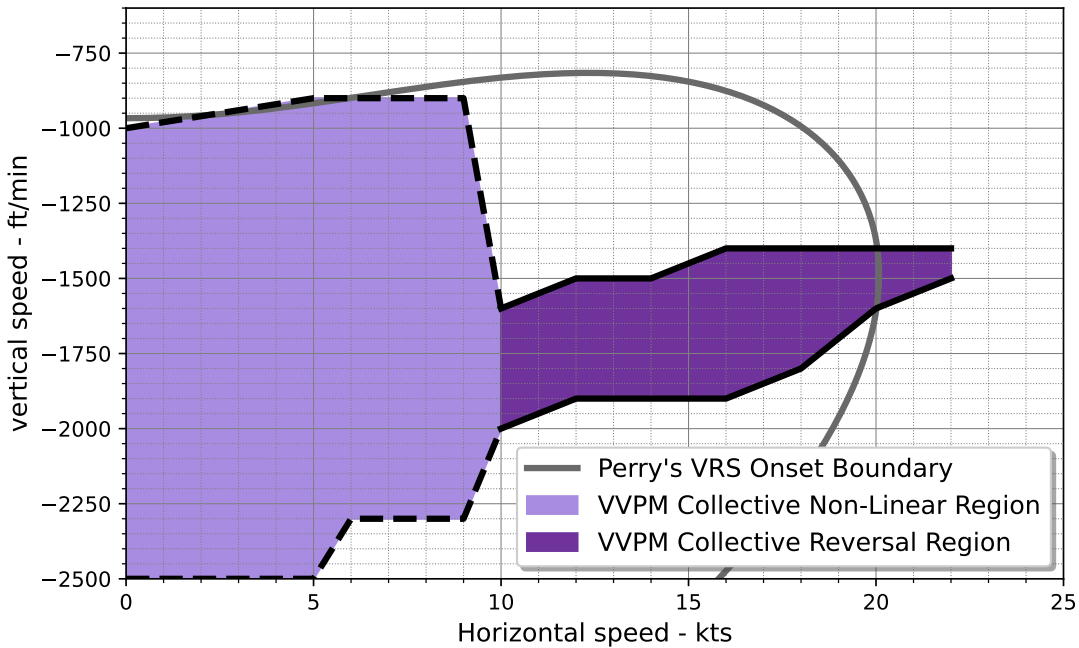


Figure 5. FLIGHTLAB Model with Dynamic inflow at medium weight - Non-linear collective behavior boundary

Finally, evaluation methods were developed and applied to the flight simulator and the two FLIGHTLAB models investigated to test for the criterion.

These methods allowed us to identify, in the simulation models, shortcomings or limitations regarding this aspect of VRS onset. The experiments showed that the non-monotonic non-injective behavior of the collective trim position with the descent rate is present in the flight simulator (but starting

at steeper descent rates than expected), and in the H125 FLIGHTLAB VVPM model (although for a smaller range of airspeeds than expected), as illustrated in Figure 7. However, the behavior is not present in the H125 FLIGHTLAB dynamic inflow model. This model thus fails the evaluation and will not be investigated further in this paper.

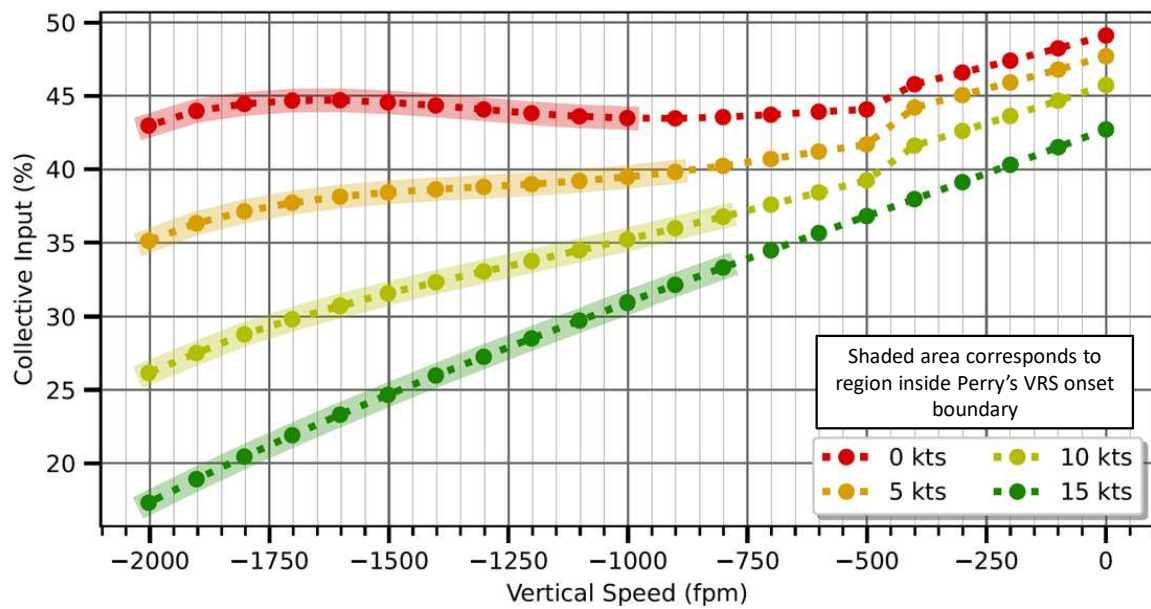


Figure 6. FLIGHTLAB Model with Dynamic inflow at medium weight - Collective input in trimmed descent

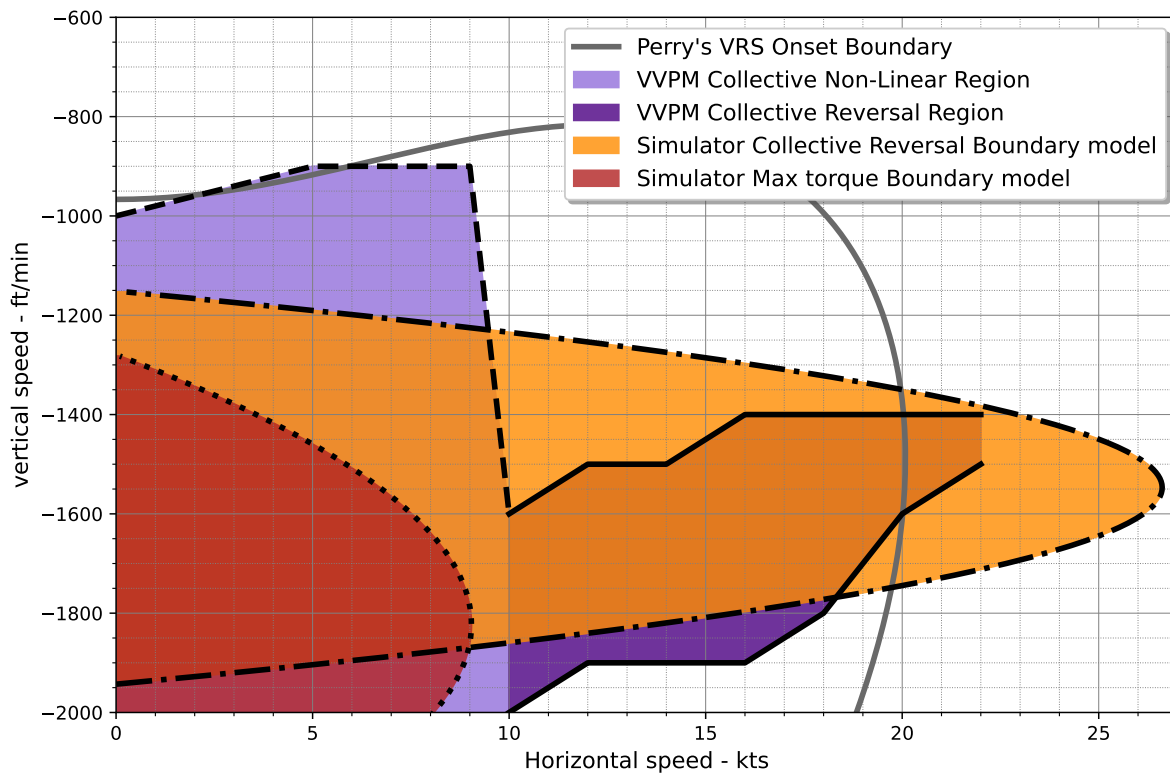


Figure 7. Collective non-linearity regions comparison - medium weight

EXPERIMENTAL RESULTS: Variations in Vertical Acceleration in Steep Descent

A prominent VRS onset cue is the fluctuation in vertical acceleration in steep descent, which results in vibrations that can help pilots identify the risk of a VRS encounter. This experiment aimed to evaluate the frequency and amplitude of the fluctuations in vertical accelerations in steep descent, depending on the airspeed and descent rate in the simulator. Following the same process as the previous task, we start by defining an evaluation criterion based on flight test results, and we then develop and apply methods to test for this criterion in the flight simulator and the simulation model investigated.

Fidelity Criterion Definition

R66 Flight Test: Experimental Method This flight test is combined with the one presented in the previous section. Since every trim position is held for a few seconds, this provides us with long enough segments of trimmed flight from which to measure the amplitude of vertical acceleration.

R66 Flight Test: Results With the helicopter's instrumentation, the acquisition frequency was only 5 Hz; for comparison, the main rotor blade passing frequency for the H125 model is 19.5 Hz. Therefore, the frequency of the vibrations is not analyzed; the results presented below focus on the amplitude of the vibrations. Having flown the R22 simulator the day before, the pilot reported a noticeable discrepancy between vibrations in the helicopter and in that simulator. In the helicopter, he noticed the first significant vibrations in vertical descent at around 300 ft/min of descent rate, whereas in the simulator, he did not perceive any until below -1000 ft/min. The example of descent presented in Figure 8 corroborates the pilot's observation concerning the helicopter, even at the shallow descent rates in these two descents, an increase in the amplitude of the vertical vibrations is observed. Figure 9 shows a heatmap of the amplitude of the fluctuations in vertical acceleration, where darker shades of blue denote higher amplitudes. Again, the increase in vibrations reported by the pilot in vertical descent at shallow descent rate is clearly visible. Surprisingly, smaller vibrations were recorded at steeper descent rates, and there is a lack of data closer to VRS onset. As a result, this flight test alone is insufficient to define our evaluation criterion, and additional data from the literature must be considered.

Literature Review In their flight test campaign, the EASA/ONERA was able to record vibrations at a sampling rate exceeding 8000 Hz (over 1600 times faster than our instrumentation). After substantial processing of the vertical acceleration data, they observed perceivable low-frequency vibrations, starting at low rates of descent, and increasing in intensity with the rate of descent (Ref. 20). Our R66 results are in agreement with this observation.

The increase in the level of vibrations was observed up to the onset of VRS, for which the average maximum peak-to-peak amplitude of the raw signal was calculated. Once in VRS, they determined that the energy was concentrated on the first two

main rotor blade harmonics, while the maximum of energy can be observed on other frequencies outside the VRS domain

From these observations, the following evaluation criterion is defined.

Fidelity Criterion If the simulation accurately represents VRS onset and entry, then there is:

- In steep descent before entering VRS: Low frequency vibrations (10 Hz to 20 Hz) that can be perceived for low RoD (from -300 ft/min), and increase in intensity when the RoD increases (from -500 to -700 ft/min)
- At the onset of VRS: An increase in the level of vibration Average maximum peak to peak P2PZ measured in the raw signal in m/s²: 0.128-0.2156 g
- Once in VRS: Energy is concentrated on the first two main rotor blade harmonics, while the maximum of energy can be observed on other frequencies outside the VRS domain

Flight Simulator Evaluation

Experimental Method Unlike in the actual helicopter, the simulator represents vertical acceleration through two distinct channels: the visual display (via the VR headset) and the motion platform. Consequently, the vertical accelerations perceived by the pilot through seat motion may differ from those conveyed visually. While the vertical acceleration from the visuals is accessible via the simulator's data recorder, no direct measurements of the motion platform's vibrations or movements are available. To address this, we installed accelerometers on the simulator seat.

Inspired by the set-up of an experiment from the German Aerospace Center (DLR) investigating motion sickness (Ref. 22), we decided to use two iPhones taped to the top and side of the simulator seat, as illustrated in Figure 10. The Physics Toolbox Sensor Suite allowed us to record accelerations with an acquisition frequency of 100 Hz.

Following the same procedure as in the collective trim section, we performed a stepped descent with the flight assistance, maintaining each step for at least 15 seconds instead of 5. The parameters used for these descents are presented in Table 3. To ensure realistic weight distribution, a passenger was seated in the simulator. This individual was also responsible for calibrating the accelerometers and managing the start and stop of each recording.

Variable	Values
Helicopter Model	H125 Flight Simulator
Forward Flight speed	0 kts - 5kts - 10kts - 50 kts
Weight	Low - Medium - High - MTOW
Descent Rate	From 0 ft/min with -200 ft/min increment until instability is reached

Table 3. Parameters to model the vertical acceleration and torque fluctuations in stabilized steep descent in a flight simulator

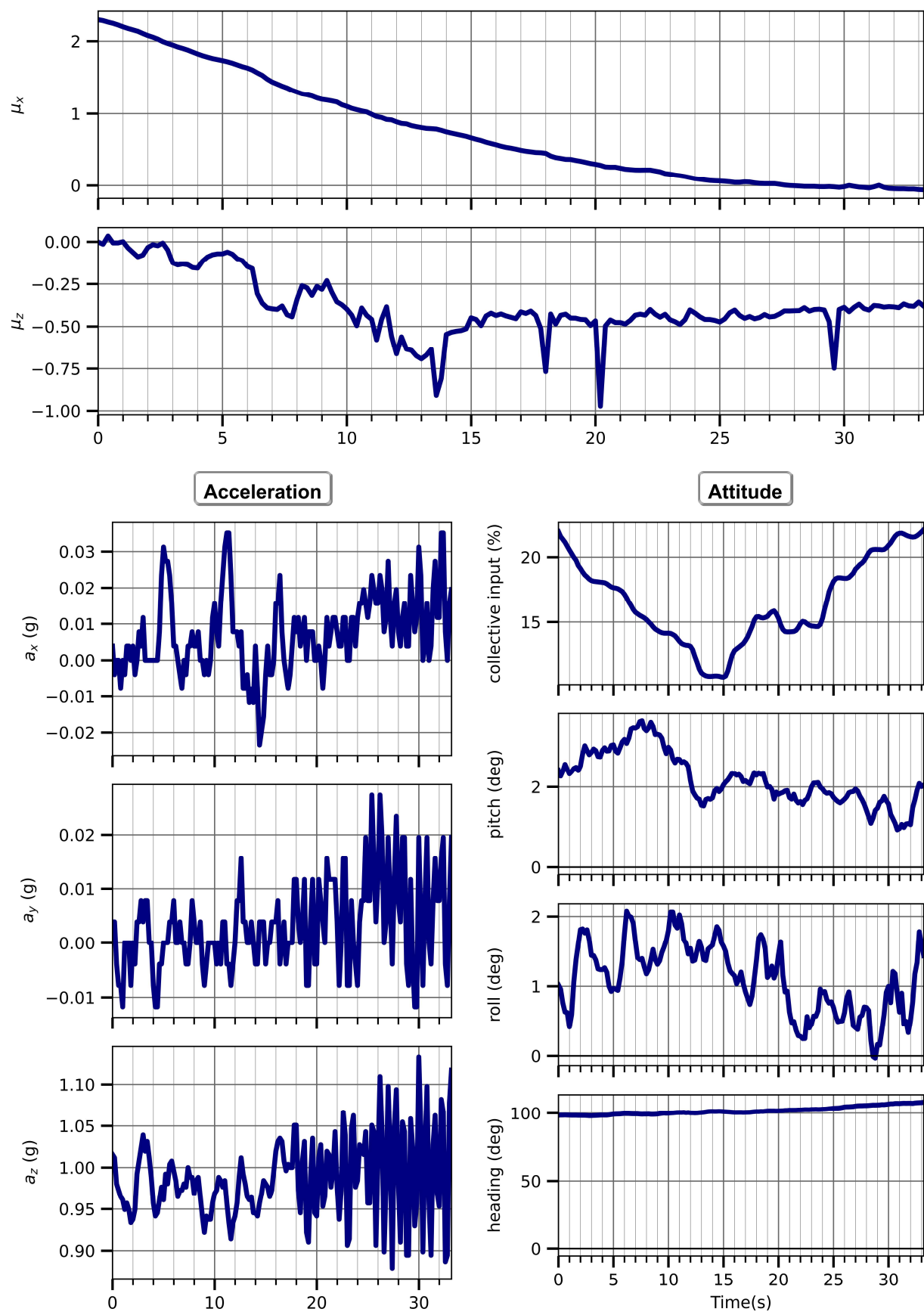


Figure 8. R66 velocity, acceleration, and attitude in stable descent

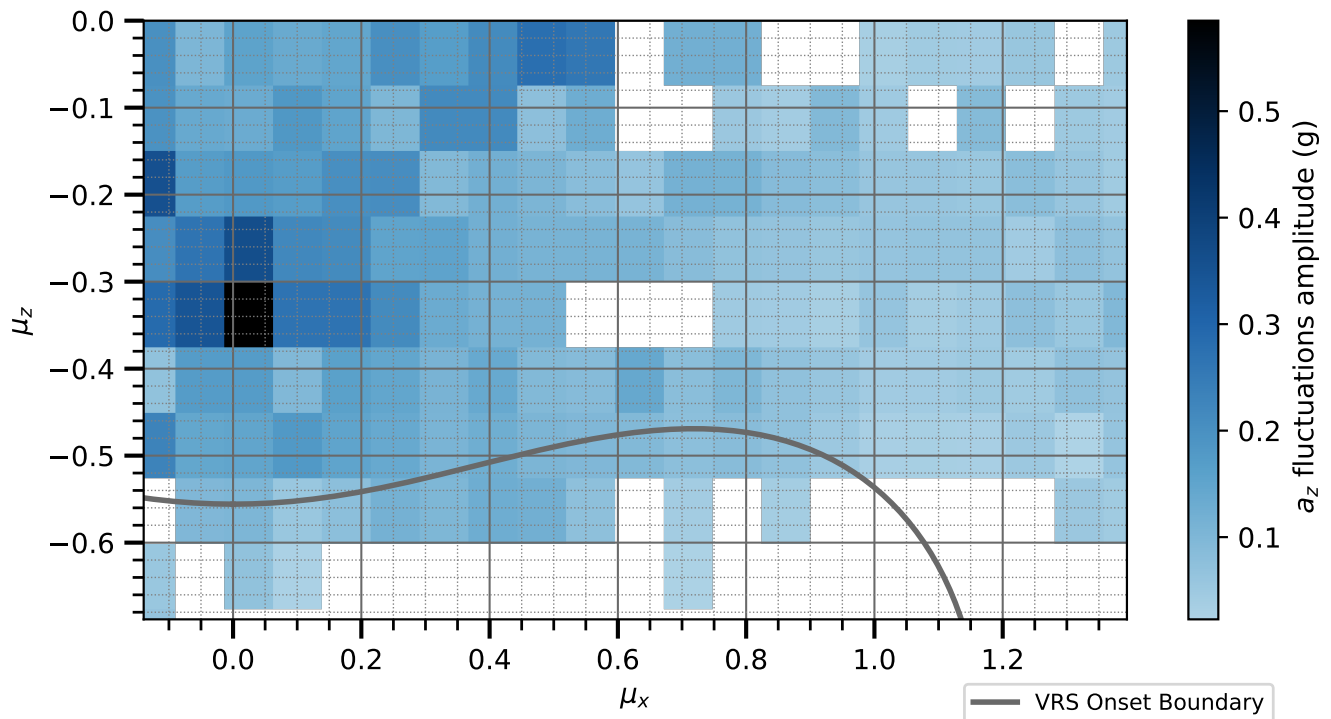


Figure 9. R66 amplitude of vertical acceleration fluctuations in trimmed flight



Figure 10. Flight Simulator Instrumentation for Acceleration Measurements

Results Before analyzing the results, data preprocessing was necessary. Specifically, the data recorded by the seat-mounted accelerometers must be synchronized and combined with the flight simulator data to allow for comparison. This was achieved using the time stamps from both datasets. The flight simulator data was then resampled to match the acquisition rate of the accelerometers. Once merged, the alignment was verified by confirming that the peaks in acceleration coincide across both sources. The resulting dataset was then segmented according to each combination of weight, forward speed, and vertical speed, in preparation for the amplitude and frequency analysis presented next.

The two accelerometers provided consistent results. However, the accelerometer mounted on the top of the seat exhibited some noise, likely caused by the passenger's upper body movement during the simulation. As a result, only the measurements from the side-mounted accelerometer are included in the analysis.

We begin by examining the amplitude of the vertical acceleration fluctuations. As shown in Figure 11, increased vibrations are observed in steep descent from the seat-mounted sensor but not from the visuals. Therefore, in this simulator, the vibratory cues are provided solely by the simulator seat and not by the VR headset, likely to avoid mismatches between visual and physical stimuli that could lead to motion sickness. For that reason, the rest of this section focuses on the measurements obtained from the motion platform.

Figure 12 shows the average, minimum, and maximum peak-to-peak amplitude of the fluctuations in the vertical acceleration measured by the accelerometer for each combination of weight, forward flight speed, and descent rate. In addition, Table 4 summarizes the overall maximum and maximum average values measured in the segments of the stepped descent segments for each weight and forward flight speed combination.

Between descent rates of -300 and -700 ft/min, no signifi-

cant increase in the amplitude of the vibrations is observed. The noticeable increase in vibrations appears to occur within the collective reversal boundary defined in the previous section. As discussed earlier, the simulator cannot be trimmed at 0 knots within this region due to a sharp and sudden increase in torque demand, which likely explains the absence of significant vibrations at that speed. From this table, the maximum peak-to-peak amplitudes recorded in the collective reversal region range from 0.20 to 0.27 g. This is within the range from our fidelity criterion (0.15 – 0.27 g).

Regarding the frequency analysis of the accelerometer data, the main rotor blade passing frequency, f_{BP} , of the H125 helicopter is 19.5 Hz, and the second harmonic, $2f_{BP}$, is 39 Hz. Given the 100 Hz acquisition frequency of the accelerometer, Power Spectral Density (PSD) analysis can be performed up to 50 Hz, which covers these first two main rotor blade harmonics.

Figure 13 shows the results of the PSD at medium weight, at 5 knots of forward flight speed at 0, -800 , and -1400 ft/min vertical speeds. The shaded orange and the yellow areas are centered on f_{BP} and $2f_{BP}$, respectively, with a 10 % margin on each side. Figure 14 and Figure 15 show the results of the PSD at medium weight for forward speeds of 5 and 50 knots at all descent rates. In all cases, distinct peaks are observed near each of the first two blade harmonics. At shallow descent rates, the energy is more broadly distributed, while in the collective reversal region, the energy becomes more concentrated around f_{BP} and $2f_{BP}$. No significant vibrations are observed at frequencies below f_{BP} in any case.

From these results, the fidelity criterion is only partially validated for this simulator. Although an increase in the amplitude of the vibrations is observed when approaching VRS, it occurs too late in the descent to serve as an early warning. Consequently, pilots using this simulator for training may not experience the early vibratory cues that could help in anticipating VRS onset.

Simulator max. average peak-to-peak amplitude of vertical acceleration in stabilized descent (g)					
Weight	Airspeed	0 kts	5 kts	10 kts	50 kts
Low		0.05	0.08	0.21	0.08
Medium		0.04	0.20	0.19	0.10
MTOW		0.03	0.03	0.16	0.07

Simulator max. peak-to-peak amplitude of vertical acceleration in stabilized descent (g)					
Weight	Airspeed	0 kts	5 kts	10 kts	50 kts
Low		0.07	0.12	0.27	0.12
Medium		0.07	0.25	0.25	0.15
MTOW		0.05	0.04	0.20	0.11

Table 4. Simulator Peak-to-Peak amplitude of vertical acceleration in stabilized descent

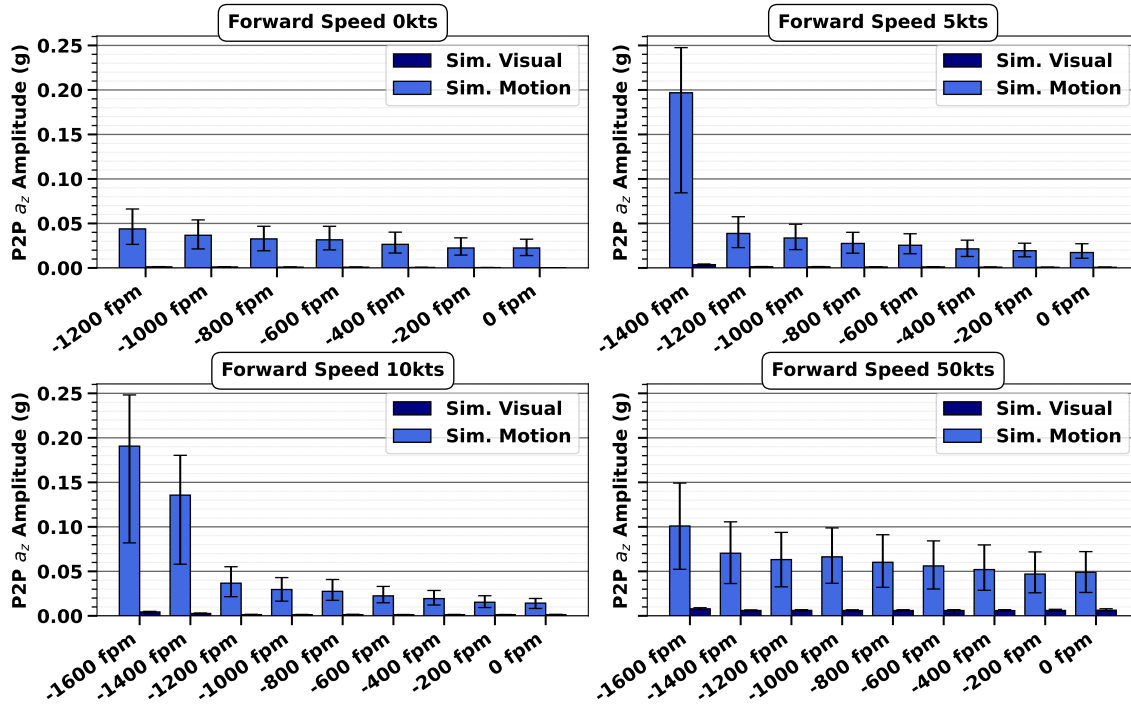


Figure 11. H125 flight simulator medium weight peak-to-peak amplitude of a_z in stabilized steep descent

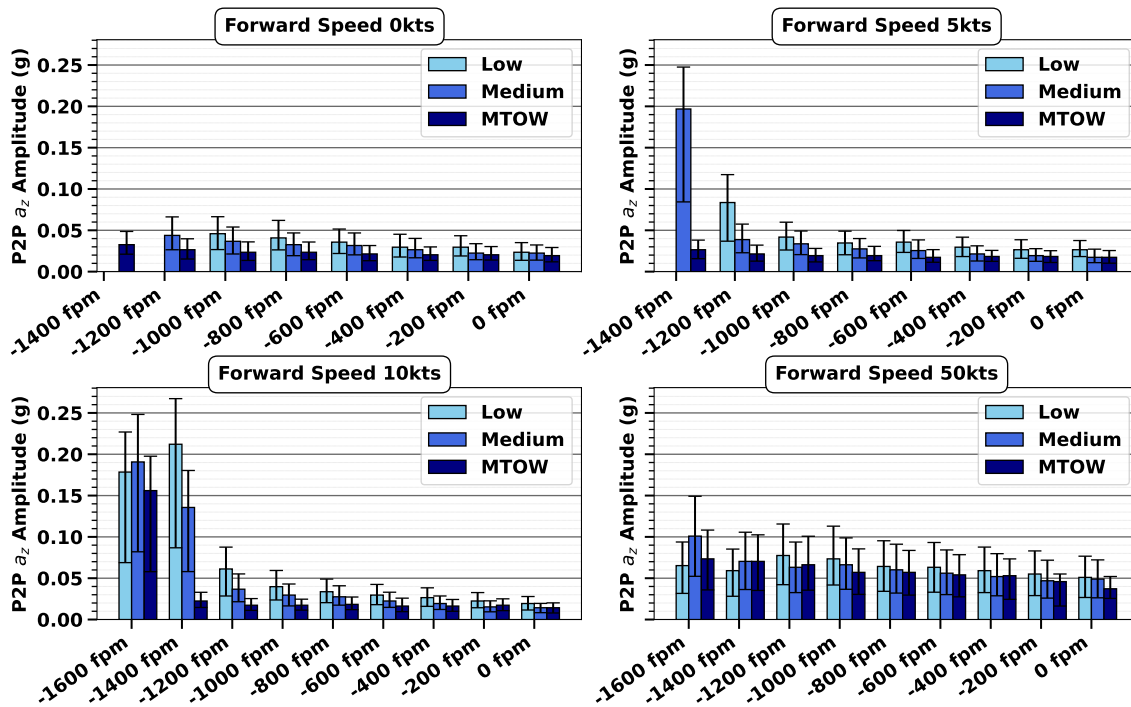


Figure 12. H125 flight simulator motion platform peak-to-peak amplitude of a_z in stabilized steep descent at various weight settings

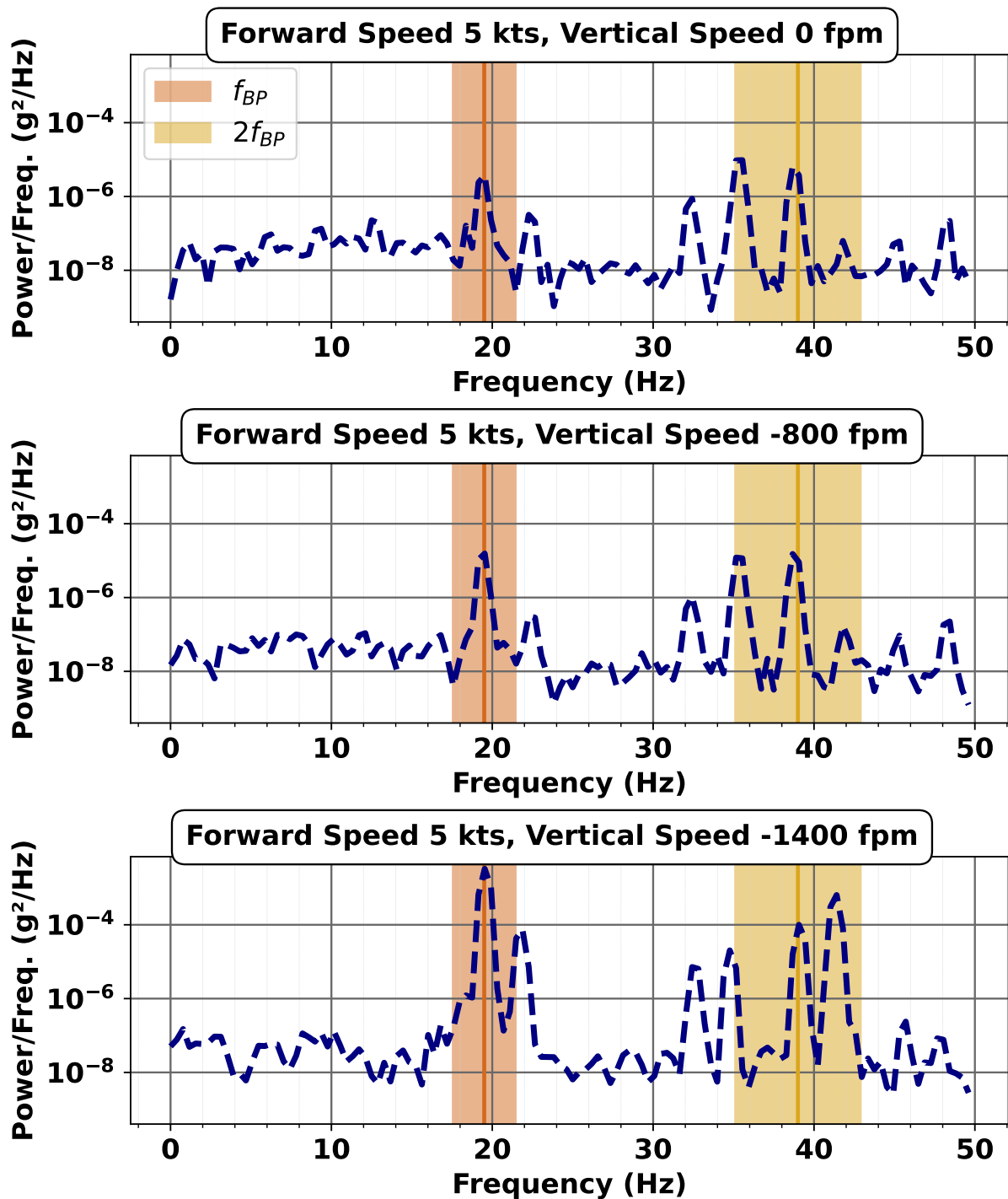


Figure 13. Simulator - PSD at medium weight, 5 knot-airspeed, and three vertical speeds

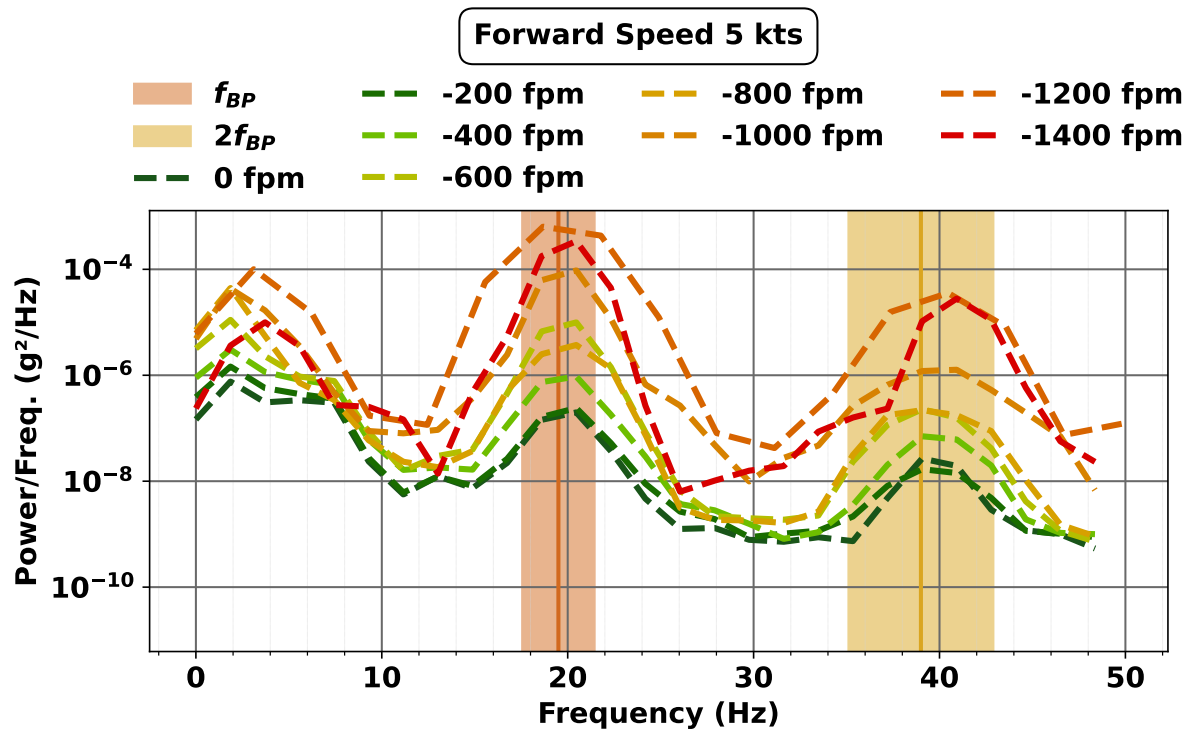


Figure 14. Simulator - PSD at medium weight, 5 knot-airspeed, and various vertical speeds

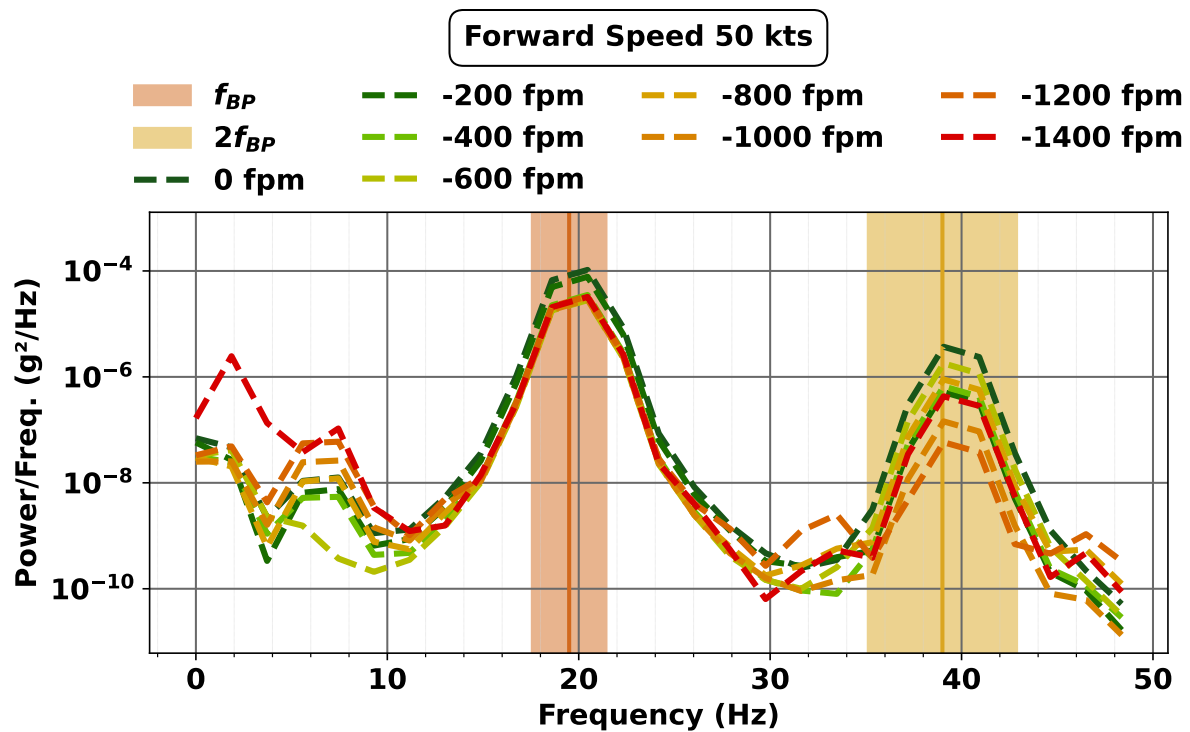


Figure 15. Simulator - PSD at medium weight, 50 knot-airspeed, and various vertical speeds

FLIGHTLAB VVPM Model Evaluation

Experimental Method Following the process described in the collective trim section, we trimmed the simulation model at each combination of weight, forward flight speed, and descent rate from Table 5. We then ran the simulation, maintaining the control inputs in the trim position, for at least two seconds, and until the model's attitude and descent rate started to deviate.

Results Starting with the amplitude of the vertical acceleration fluctuations, Figure 16 shows the average, minimum, and maximum peak-to-peak values at each combination of weight, forward flight speed, and descent rate. In addition, Table 6 summarizes the overall maximum and maximum average for each weight and forward flight speed configuration. A gradual increase in the amplitude of the vertical vibrations with the increase in descent rate is observed at 0, 5, and 10 knots. Moreover, at all weights, at and below 10 knots, the maximum peak-to-peak amplitude of the vertical acceleration is between 0.115 and 0.218 g. This is within the range of the fidelity criterion, except for the value at medium weight at 10 knots.

Regarding the frequency analysis, Figure 17 shows the results of the PSD at medium weight, at 5 knots of forward flight speed at 0, -800, and -1400 ft/min vertical speeds. Following the same format as the simulators' results, the shaded orange and yellow areas are centered on f_{BP} and $2f_{BP}$, respectively, with a 10 % margin on each side. Figure 18 and Figure 19 show the results of the PSD at medium weight with forward flight speeds of 5 and 50 knots at all descent rates. In all cases, peaks are observed around the first two main rotor blade harmonics. At 5 knots, the peaks increase with the increase in descent rate. At and below -800 ft/min, the highest peak is at the main rotor blade passing frequency, whereas at shallower descent rates it is at around 2 Hz. In addition, at this speed, a third peak is observed below 5 Hz.

From these results, our fidelity criterion is only partially validated for this model as well. In steep descent, for descent

rates above around 400 to 800 ft/min, an increase in the intensity of the vibrations with the rate of descent is observed, as required. However, the frequency of these vibrations is predominantly below 5 Hz instead of between 10 and 20 Hz. At the steeper descent rates, the criterion is validated. Indeed, at the onset of VRS, between -800 and -1400 ft/min, the range of peak-to-peak maxima is mostly within the range from the fidelity criterion. Finally, at -1400 ft/min, the power/frequency is concentrated on the first two main rotor blade harmonics, whereas the power/frequency is more evenly spread at lower descent rates.

Outcome

Our goal was to define and apply a method assessing the representation of vertical vibrations in steep descent for the flight simulation models evaluated. We achieved it by first designing a flight test plan to determine the variations in trimmed collective position in steep descent as a function of forward flight speed and descent rate. This plan was then tested in an instrumented helicopter; unfortunately, the results, when approaching VRS, were inconclusive. Therefore, our fidelity criterion for the vertical vibrations in steep descent was instead derived from flight test results found in the literature. Finally, evaluation methods were developed and applied to the flight simulator and the FLIGHTLAB model investigated to test for the criterion.

These methods allowed us to identify, in the simulation models, shortcomings or limitations regarding this aspect of VRS onset. The experiments showed that both partially verify the fidelity criterion. In the simulator, although an increase in the amplitude of the vibrations is observed when approaching VRS, it occurs too late in the descent, which could lead to negative training. With the FLIGHTLAB model, near VRS onset, both amplitude and frequency characteristics met the fidelity criterion. At shallower descent rates, the model captured the amplitude trend well, but with lower-than-expected frequencies.

Variable	Values
Helicopter Model	H125 model VVPM
Forward Flight speed	0 kts - 5kts - 10kts - 50 kts
Weight	Low - Medium - High - MTOW
Descent Rate	0 ft/min to -1600 ft/min, 200 ft/min increment

Table 5. Parameters to model the vertical acceleration and torque fluctuations in stabilized steep descent in FLIGHTLAB

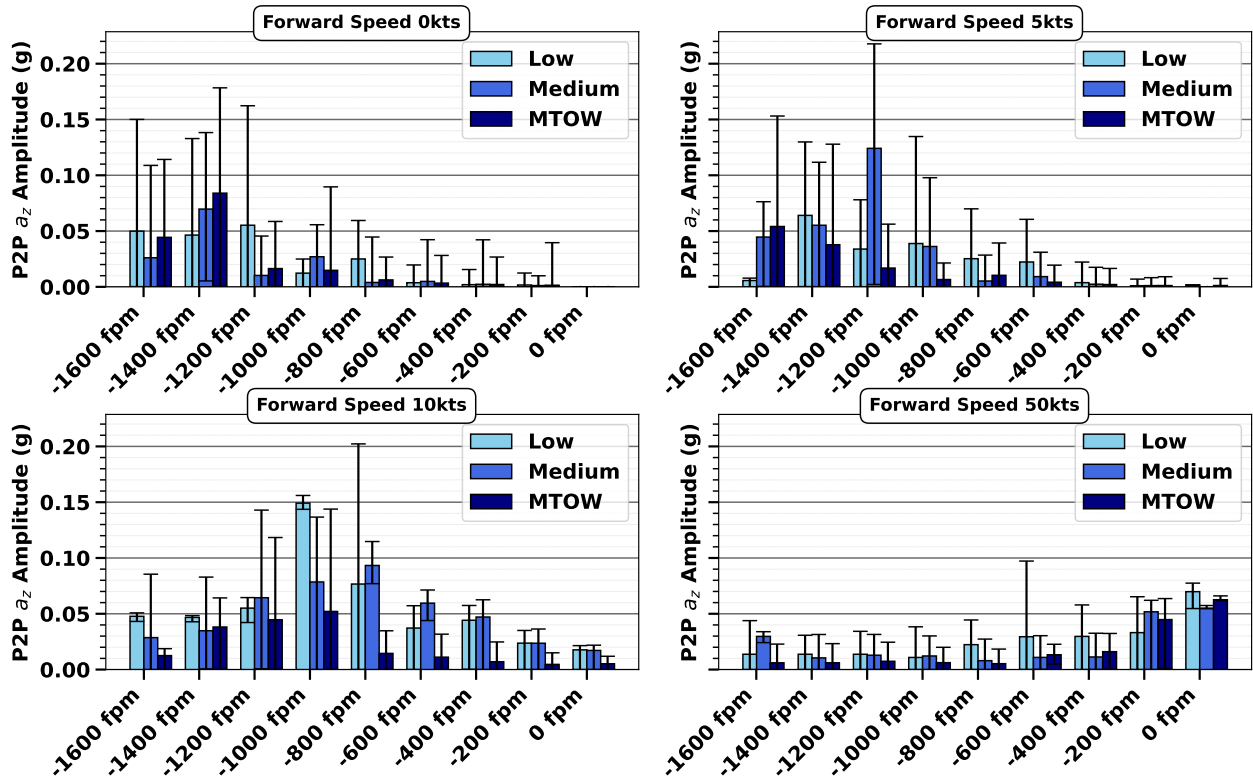


Figure 16. H125 FLIGHTLAB VVPM model - amplitude of fluctuations in vertical acceleration in trimmed descent

FLIGHTLAB VVPM max. average peak-to-peak amplitude of vertical acceleration in stabilized descent (g)					
Airspeed					
Weight	0 kts	5 kts	10 kts	50 kts	
Low	0.055	0.064	0.149	0.07	
Medium	0.07	0.124	0.0933	0.0551	
MTOW	0.084	0.0541	0.052	0.0626	

FLIGHTLAB VVPM max. peak-to-peak amplitude of vertical acceleration in stabilized descent (g)					
Airspeed					
Weight	0 kts	5 kts	10 kts	50 kts	
Low	0.162	0.1299	0.156	0.077	
Medium	0.138	0.218	0.115	0.057	
MTOW	0.178	0.153	0.144	0.66	

Table 6. FLIGHTLAB VVPM Peak-to-Peak amplitude of vertical acceleration in stabilized descent

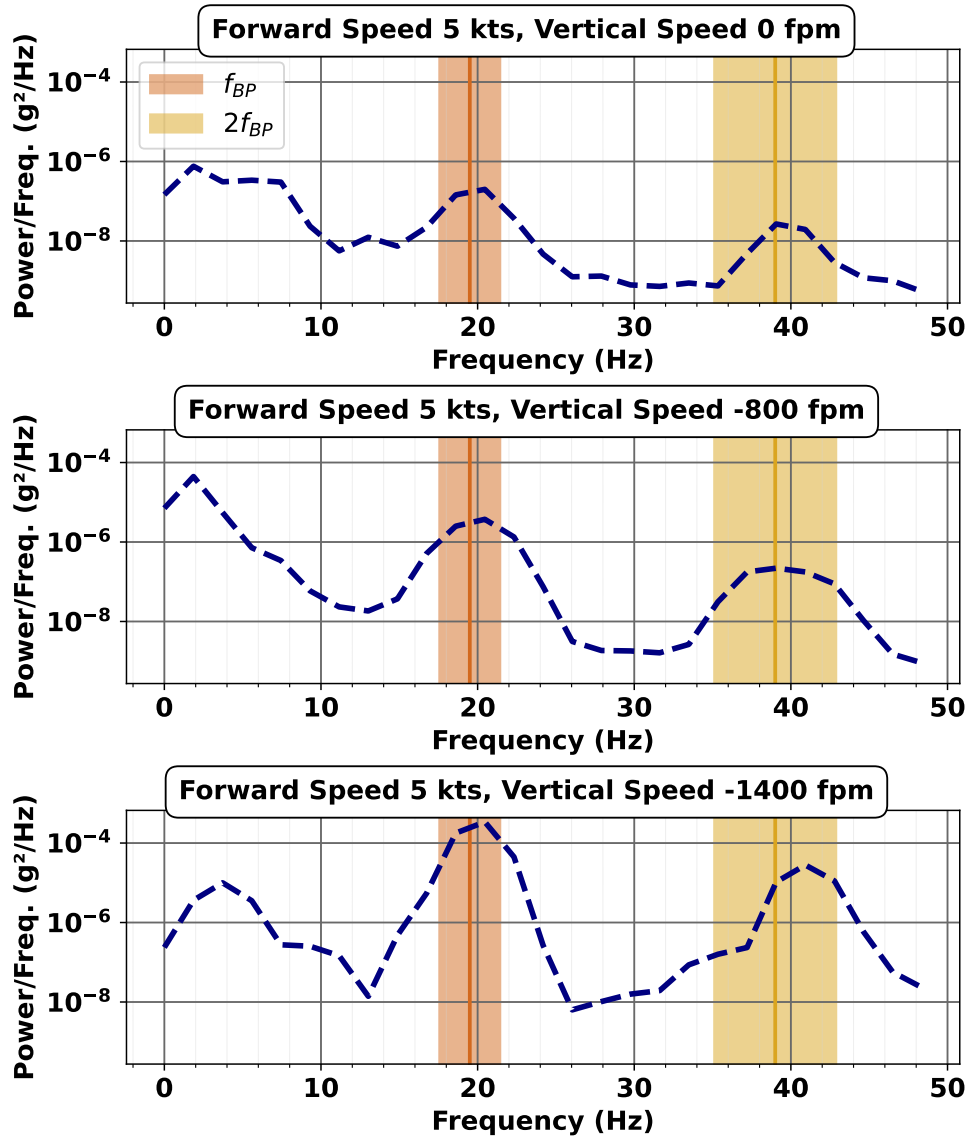


Figure 17. FLIGHTLAB VVPM PSD at medium weight, 5 knot-airspeed, and three vertical speeds

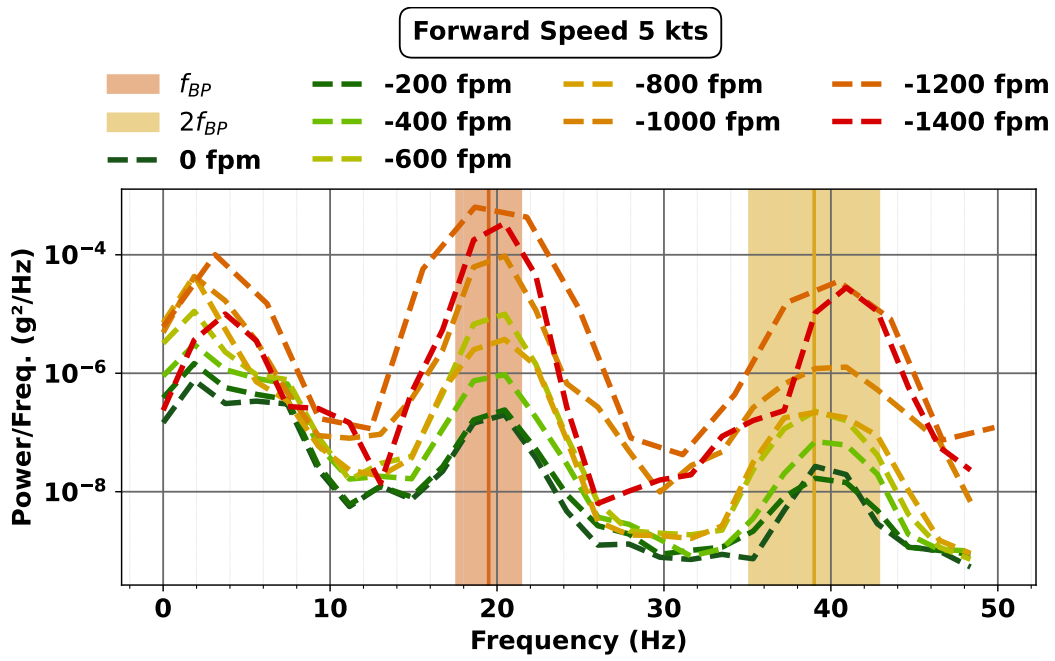


Figure 18. FLIGHTLAB VVPM PSD at medium weight, 5 knot-airspeed, and various vertical speeds

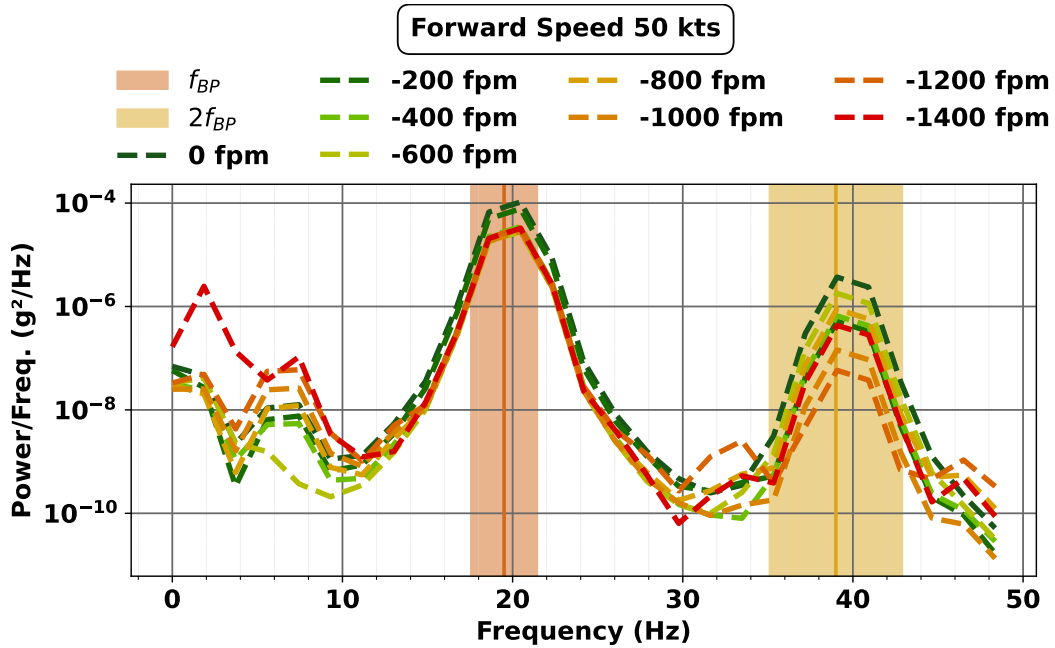


Figure 19. FLIGHTLAB VVPM PSD at medium weight, 50 knot-airspeed, and various vertical speeds

EXPERIMENTAL RESULTS: VRS ENTRY MANEUVER

This section aimed to evaluate the evolution in descent rate when entering VRS from the upper limit and from the side of the VRS onset boundary.

Following the same process as the previous tasks, we started by defining an evaluation criterion based on flight test results, and we then developed and applied methods to test for this criterion in the flight simulator and the simulation model investigated.

Fidelity Criterion Definition

During the flight test performed on the Robinson R66, steep descents were performed, but the descent rate was not increased enough to observe a sudden drop in vertical speed. Hence, no flight test data, which could be used for this task, was collected. The evaluation criterion defined in this section will thus rely solely on the literature review.

Literature Review The ONERA/CEV performed a flight test campaign in the early 2000s on VRS. They observed that at the onset of VRS, any light reduction of the collective will lead to a new trim condition corresponding to a much higher rate of descent, leading to an abrupt increase in the vertical speed (Ref. 23), (Ref. 24). This is the most noticeable and well known characteristic of the VRS entry. Based on this observation, the corresponding evaluation criterion is defined below.

Fidelity Criterion If the simulator accurately represents VRS onset and entry, then there is a sudden and uncontrolled increase in descent rate when entering VRS from any part of the VRS onset boundary.

Flight Simulator Evaluation

Experimental Method Following the same method as the EASA/ONERA (Ref. 20), two types of entry maneuvers are considered: vertical entries (entering from "above the VRS boundary", meaning maintaining a constant forward flight speed and continuously increasing the rate of descent) and decelerated entries (entering from the "side of the VRS boundary", meaning, starting at a high forward flight speed at a steep descent rate, maintaining the descent rate while slowing down to 0 knots).

All maneuvers were performed at a constant weight (low, medium, and maximum) starting at 3000 ft/AGL with the flight assistance enabled. As explained in the previous section, this process allowed the simulator operator to control the forward flight speed, lateral speed, vertical speed, and yaw rate from the operating station. For vertical entries, at three forward flight speeds (0, 5, and 10 knots), the simulator was started at 0 ft/min. The vertical speed was then decreased at a constant rate while maintaining the airspeed, using the flight

assistance. For decelerated entries, the simulator was started at 50 knots at two different vertical speeds (-1400 ft/min and -1800 ft/min). The airspeed was then decreased at a constant rate while maintaining the vertical speed, using the flight assistance.

Using the same instrumentation as described in the previous section, the vertical acceleration of the motion platform was measured for each maneuver.

Results Figure 21 and Figure 22 present the vertical and decelerated entries recorded in the flight simulator at medium weight. As shown previously, the flight assistance sets the flight control inputs based on speed targets given by the operator. This means that, in steep descents, in the collective reversal region, the flight assistance increases the collective input until maximum torque is reached. At this point, the collective position is adjusted to avoid overtorque. When looking at the top plots of each figure, a clear drop in the vertical speed is observed at around 30 seconds in all cases.

Figure 20 shows the minimum and maximum vertical accelerations measured in the simulator visuals and from the two accelerometers stuck to the motion platform (as described earlier, and labeled side sensor and seat sensor). The physical limitations of the reduced motion platform in terms of amplitude and speed of the vertical movements imply that the representation of the drop in vertical speed mostly comes from the simulator visuals, contrary to the vibrations from the previous section. Indeed, in all subplots, the maximum vertical acceleration values (a_z) of the motion platform are about half that of the visuals. In addition, the motion platform is limited by the length of the struts. Therefore, after the initial abrupt increase in descent rate, the motion platform has to stop the downward motion, resulting in a slight negative acceleration observed for the minimum a_z , whereas the acceleration simulated in the VR headset remains positive. This mismatch between visual and physical cues may contribute to motion sickness experienced by pilots in the simulator.

Overall, in this simulator, the sudden and abrupt increase in the rate of descent associated with VRS is simulated, primarily in the VR headset visuals and less significantly by the motion platform, when entering vertically or with a horizontal deceleration, at all weight settings. Thus, the fidelity criterion is verified.

FLIGHTLAB VPPM Model Evaluation

Experimental Method Following a similar approach to the flight simulator's experiment, vertical and decelerated entries with the FLIGHTLAB model must be simulated. Due to difficulty in properly tuning the flight control inputs over an extended duration using the PID controller strategy described in (Ref. 18), only two descents were modeled, at medium weight: a vertical descent at 0 knots and a decelerated descent at -1500 ft/min. First, for each descent, the model is trimmed following the process described earlier, at 0 knots and -800 ft/min for the vertical descent, and at 30 knots and

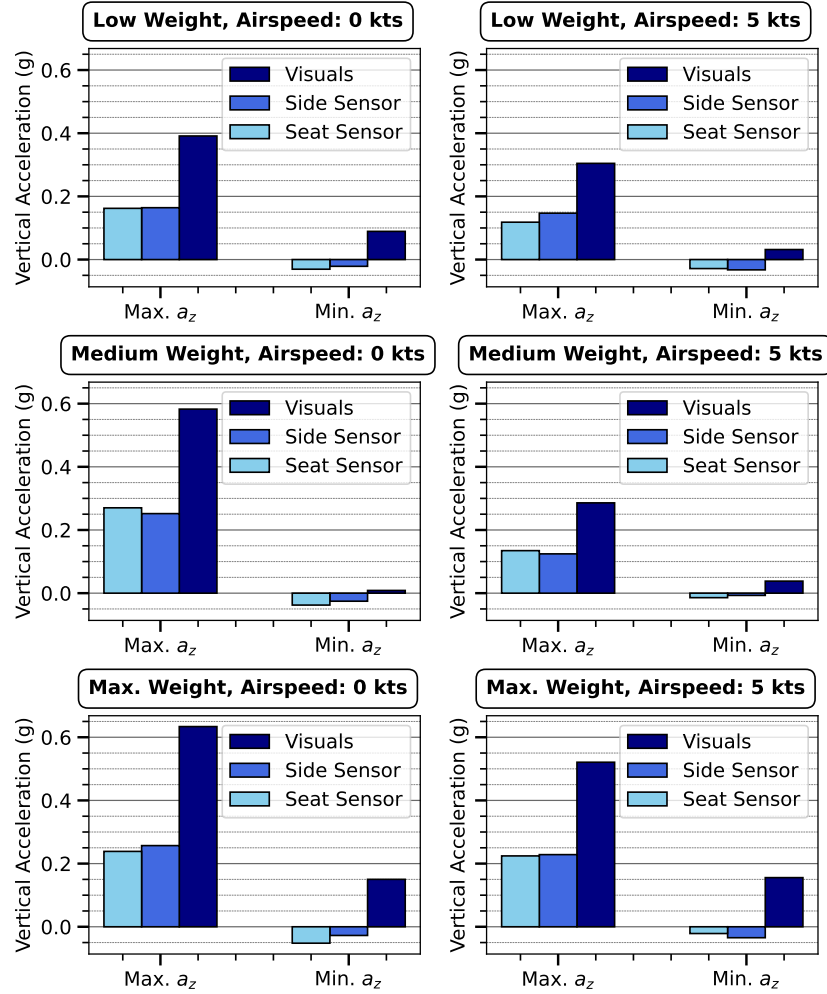


Figure 20. H125 Simulator at Medium weight, VRS Entry a_z variations (g)

-1500 ft/min for the decelerated descent. In both cases, this places us outside of the collective non-linear region identified previously. Then, the controller gains and targets are tuned until the desired descent behavior is obtained.

Results Figure 23 presents the vertical and decelerated entries recorded in the flight simulator at medium weight. When looking at the top plots, an abrupt drop in the vertical speed is observed, starting at around 2 seconds for the vertical entry and around 22 seconds for the decelerated one. In addition, Table 7 displays the minimum and maximum vertical acceleration measured in both simulations.

Overall, the sudden and abrupt increase in the rate of descent associated with VRS is simulated with this FLIGHTLAB model for both entries. Therefore, the fidelity criterion is verified.

Outcome

Our goal was to define and apply a method assessing the representation of the drop in vertical speed in steep descent for

Entry	Min. Vertical Accel. (g)	Max. Vertical Accel. (g)
Vertical Entry - 0 kts	-0.08	0.34
Decelerated Entry - 1400 ft/min	-0.10	0.16

Table 7. Vz Drop: VVPM model Vertical Acceleration for entry maneuvers

the flight simulation models evaluated. We achieved it by first deriving a fidelity criterion from flight test results found in the literature. Then, evaluation methods were developed and applied to the flight simulator and the FLIGHTLAB model investigated, to test for the criterion.

These methods allowed us to identify, in the simulation models, shortcomings or limitations regarding this aspect of VRS onset. The experiments showed that, for both models, a vertical speed drop is observed both when descending vertically and with a horizontal deceleration. In addition, in the simulator, this drop is represented primarily by the visuals and to a lesser extent by the motion platform.

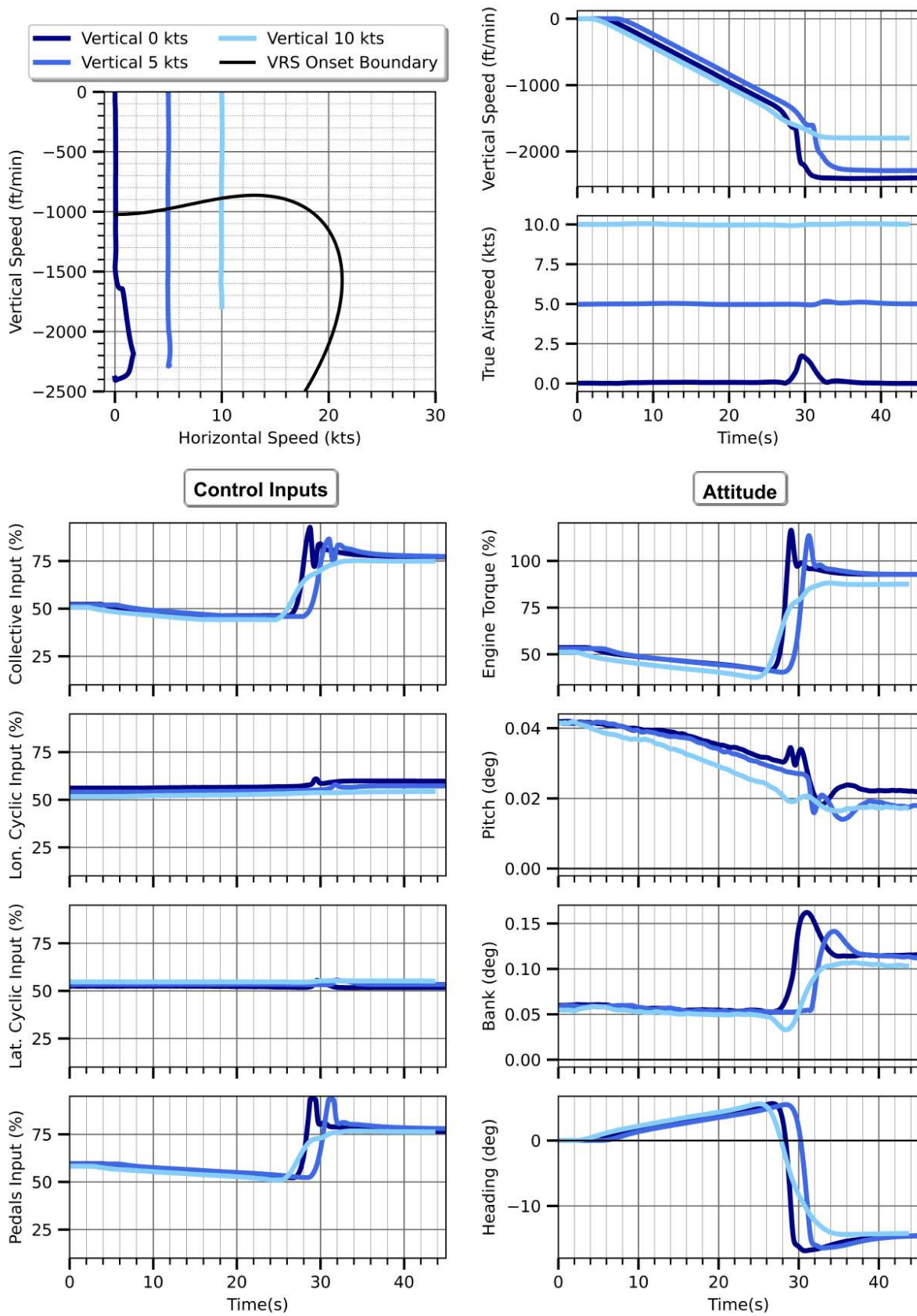


Figure 21. H125 Simulator at Medium weight, VRS Vertical Entries

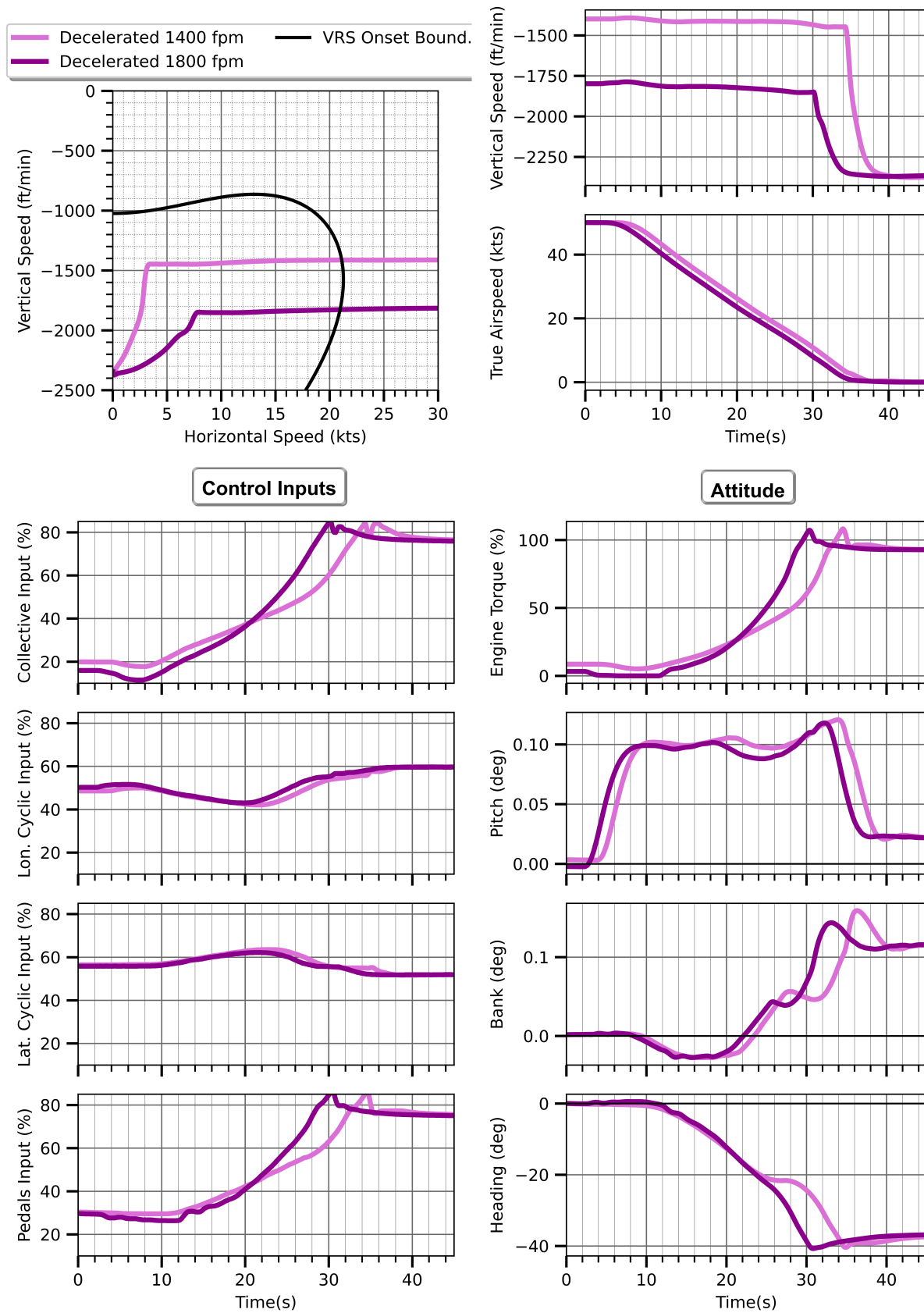


Figure 22. H125 Simulator at Medium weight, VRS Decelerated Entries

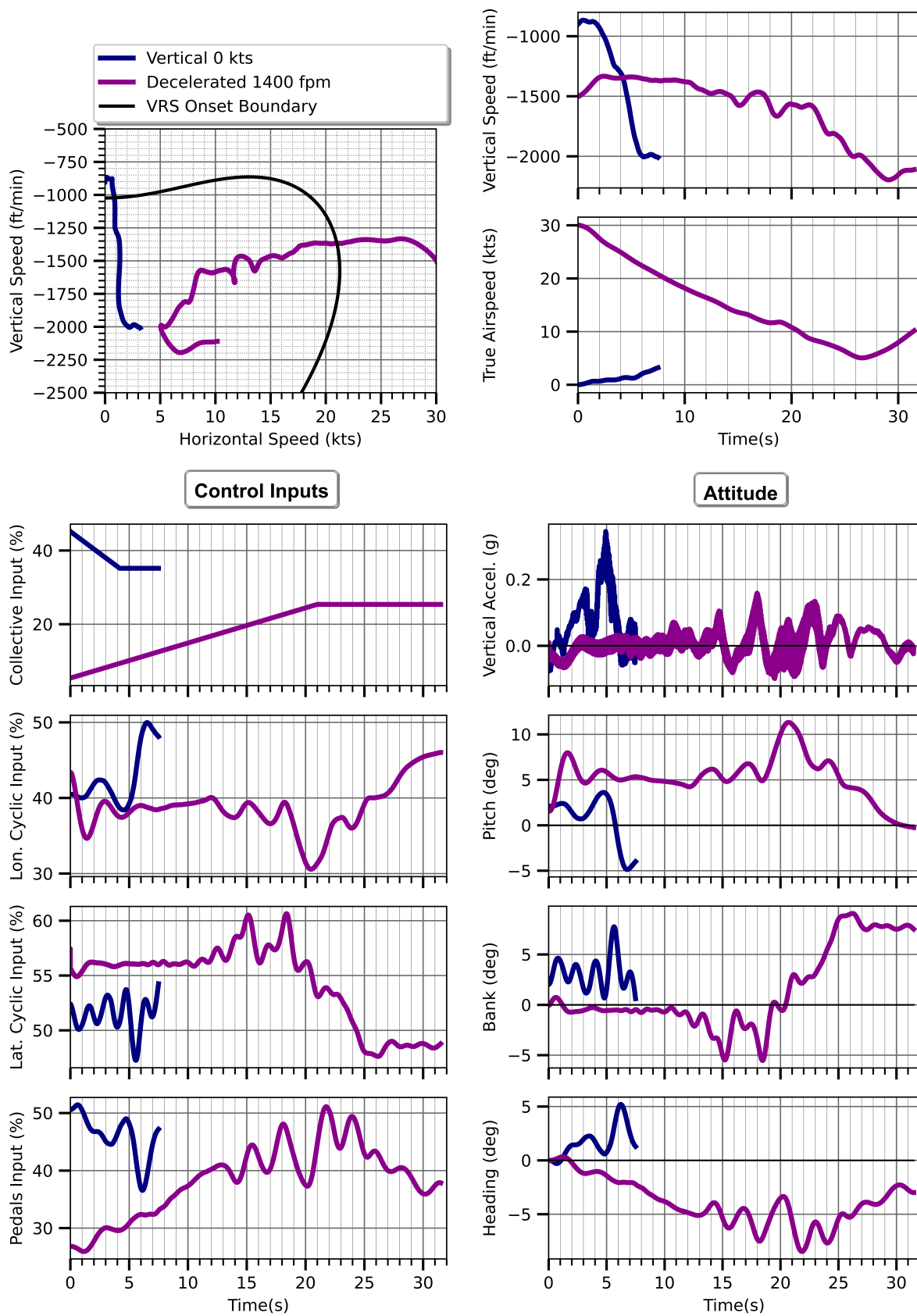


Figure 23. H125 FLIGHTLAB VVPM model at Medium weight, VRS Entries

CONCLUSIONS

This work developed a novel objective evaluation method of how well different simulation models represent the onset characteristics of VRS, to complement the current subjective assessment used for simulator qualification. Based on results from a dedicated flight test campaign and flight data from the literature, we established fidelity criteria for key onset cues. When applied to a flight simulator and two FLIGHTLAB models, we showed that our method captured meaningful limitations in each model investigated, identifying whether they are suitable for VRS simulations.

Three simulation models of varying complexity and application contexts were evaluated to assess their fidelity in representing the VRS phenomenon. The first is a commercial H125 VR reduced-motion flight simulator by Loft Dynamics, representative of the new generation of simulator technology. The second is an in-house H125 FLIGHTLAB model using the Peters-He dynamic inflow, a widely used but simplified approach that may underrepresent VRS aerodynamics. The third is a more advanced FLIGHTLAB VVPM, which better captures complex vortex dynamics but is not yet real-time capable. The evaluation of these models aimed to improve the assessment of current training technologies and inform the development of future real-time simulation models.

Three VRS onset characteristics were observed: the collective trim position, the fluctuations in vertical acceleration, and the sudden increases in descent rate. A flight test was performed in an instrumented helicopter, but results near VRS were insufficient, so they were complemented with flight test data from the literature to derive a fidelity criterion for each of these characteristics. When evaluating our simulation models with these criteria, we showed that the simulator and the FLIGHTLAB VVPM model replicated the expected behavior, with some notable limitations: a delayed onset of vibratory cues in the simulator and a correct behavior limited to a range of very low airspeeds for the VVPM model. The dynamic inflow model failed to capture the characteristic collective behavior and was excluded from further analysis.

However, satisfying all these criteria is not sufficient to guarantee a fully accurate flight simulator, as other aspects of VRS onset have not been addressed. This work focused on only three critical aspects of the onset. Hence, following the evaluation process designed and applied in this work, other characteristics of VRS could be evaluated, such as the changes in acoustic noise, and the sudden roll, pitch, and yaw motion at entry.

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