TUNING OF MOTION CUEING FILTERS FOR VIRTUAL REALITY FLIGHT SIMULATORS

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ABSTRACT

This paper describes a practical implementation of a research flight simulator used as a test bed for piloted rotorcraft, which incorporates a motion platform system and Virtual Reality (VR) visualisation software developed in-house. The work involves integrating the motion platform with the flight model, performing safety assessments and validation, and tuning the motion cues. The motion system was characterised experimentally and evaluated with criteria found in literature, which have identified deficiencies in the translational degrees of freedom. Basic pilot evaluation has focused on other issues, with little feedback about the motion cues themselves; thus, the tuning was limited to adjusting the overall gain for the motion platform. These preliminary results suggest a preference for lower intensity movements, which some unique features of this VR-based setup can explain.

INTRODUCTION

This paper describes a practical implementation of a research flight simulator used as a test bed for Rotorcraft Certification by Simulation (RoCS) (Ref. 1) and Rotorcraft-Pilot Coupling (RPC) (Ref. 2). The simulator incorporates a motion platform system and Virtual Reality (VR) visualisation software developed in-house. The work involves integrating the motion platform with the flight model, conducting safety assessments and validation, and fine-tuning the motion cues.

Virtual Reality environment is used to make the simulator experience more immersive for the pilots by increasing the realism and thus applicability of human-in-the-loop experiments. Here specifically, the VARJO XR-3 headset is used (see Figure 1), which has a resolution of 70 pixels per degree and a Field of View (FoV) of 115°. Meanwhile, a normal human FoV is about 200° horizontally and 160° vertically. So, even though VR is providing full surround situational awareness, the peripheral vision, which is more important for motion perception (Ref. 3) differs significantly from real flight conditions. Additionally, the pilots often feel the high weight of the head-mounted display used, which may also affect the proprioceptive cue of head weight as felt by the neck muscles (Ref. 4).

These factors, together with the relative time synchronisation of the flight model, the visualisation, and the motion platform responses may all affect the motion perception by pilots. As previously investigated in the literature (Refs. 5, 6), the algorithm that approximates the aircraft vestibular cues using devices with limited travel, has inherent tradeoffs that depend on all senses participating in motion perception. As such, the tuning of the washout algorithm should be done with the specific VR system used to get the best results.

SIMULATION ENVIRONMENT

The flight simulator was set up using the MARSH framework (Ref. 7), developed by authors specifically to enable testing of different motion cueing methods for simulated helicopter flight.

As shown in Figure 2, the system has an architecture consisting of decoupled components, centralised around a single application that orchestrates communication and provides synchronised data log. The pilots control the model using accurate mechanical reproduction of cyclic, collective and pedal inceptors of a generic helicopter. The only adjustments are done with a balancing spring for the collective lever and friction rings for all the axes, without any active control loading device.

The helicopter model flown by pilots is formulated as a series of state-space linear models identified from flight data (Ref. 8). At any given moment, the state-space matrices used are interpolated between the closest predefined models

Figure 1. Photo of a participant in the pilot seat on the motion platform, wearing the Head-Mounted virtual reality display

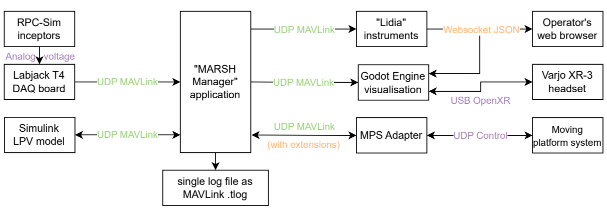

Figure 2. System architecture diagram

based on current airspeed, thus creating a Linear Parameter-Varying (LPV) model (Ref. 9).

To improve the applicability of the models to piloted flight, the models have been extended with a Stability Augmentation System (SAS). The SAS is implemented using a PID controller for each axis that is tuned in such a way as to make the complete system stable, unlike the bare airframe. Finally, the integration of all attitude angles has been separated from the internal state vector (denoted x in $\dot{x} = Ax + Bu$ equation), and handled with quaternion multiplication instead. This way, an otherwise linear model can exhibit the expected cross-axis coupling in non-level flight.

The visualisation application for VR and flat screen is developed using an open source video game engine (Ref. 10), shown in figure 3. It is also available for reuse under the terms of the MIT license (Ref. 11).

To aid in evaluating the performance between different configurations, Mission Task Elements (MTEs) defined in ADS-33 (Ref. 12) were used. These have been found to be well known by test pilots, and additionally provide specific limits for what constitutes desired and adequate performance, shown as cones and other markers as seen in Figure 3.

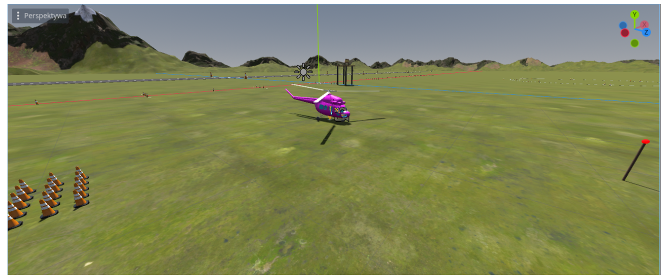

Figure 3. Screenshot of the visualised environment as seen in Godot Engine editor

MOTION CUEING

The pilot seat and control inputs are mounted on a 6-degree-of-freedom actuated platform, specifically designed for vehicular simulators as seen in figure 1. It is controlled over a network, and the simulated aircraft state is sent to the platform firmware at 100 Hz. The reports of the platform's state based on built-in encoders are received and logged at the same frequency. The delay in the motion system response has been estimated to be approximately 100 ms, which meets the limits established by the regulation for certified usage (Refs. 13,14).

The safety of the participants has been ensured with a thorough risk analysis and a semi-automated test procedure shown in Figure 4. The testing consists of sending erroneous or extreme motion commands to the system, and manual evaluation of responses by the operator. Additionally, our own software for platform control has been developed with compile-time physical quantity validation and automated unit testing.

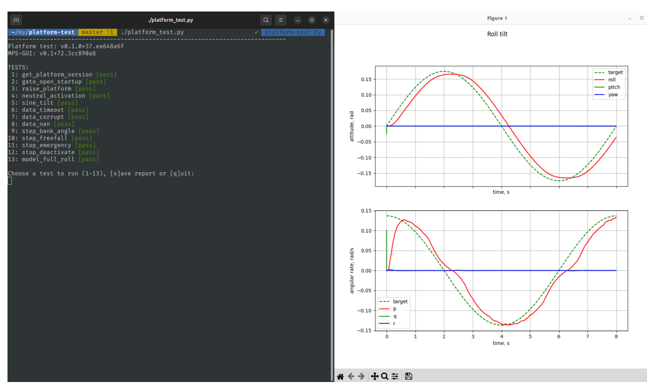

Figure 4. Screenshot of the safety test program showing a plot of roll response

System identification

Platform hardware already incorporates a proprietary washout filter, specific parameters of which are not available at the time of writing. Because it is also not modifiable in the current experimental setup, the filter was characterised experimentally. Since the form of the filter is unknown, a sinusoidal signal in a single axis of motion with stepped frequency was chosen, which can be seen in figure 6. This way, the analysis can consider steady state response to a given frequency by discarding the first few cycles of every step.

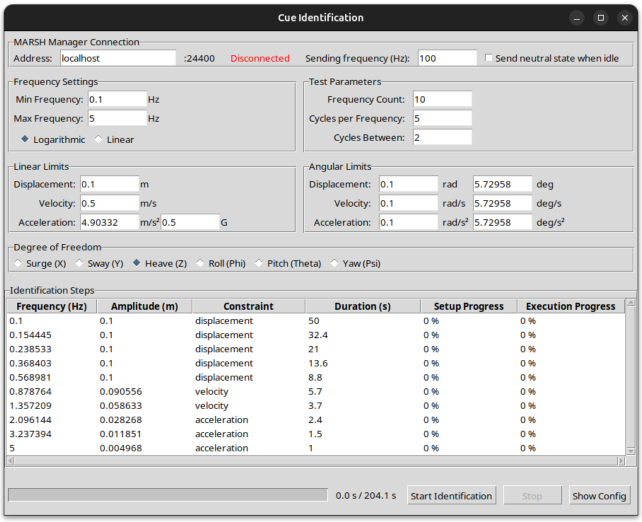

Figure 5. Settings for system identification

For reasons of safety and hardware limitations, the motion system includes limits on its travel, velocity and acceleration, which are applied in series to the main washout filter. In order to minimise the effect of these, but provide a good signal-to-noise ratio, the generated signal also has limited amplitude and derivatives. The specific settings shown in Figure 5 were found experimentally by reducing various limits, until the plotted time response is not distorted from sinusoidal.

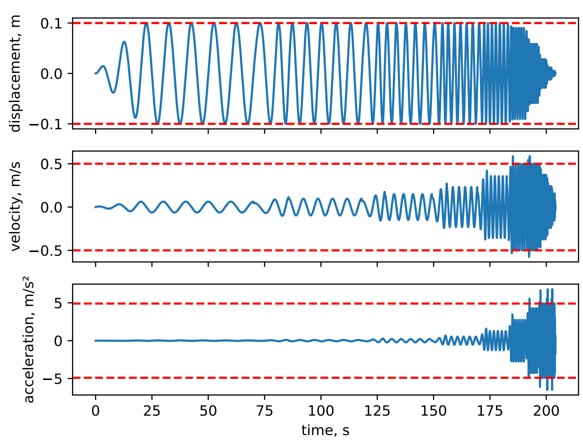

Figure 6. Example sweep signal

Based on this experiment, the system exhibited generic high-pass behaviour, so additional trials were performed to cover the frequencies from 0.01 to 8 Hz.

The controller used in the actual system is a form of multiple-input-multiple-output (MIMO) filter that drives the actuators with a compromise between the desired position, velocity and acceleration for all axes of motion. The analysis performed here assumes the following simplifications:

- Every axis is analysed separately
- A single signal or its derivative is considered
- The filter is formulated as a Laplace transfer function

Based on these assumptions, the best fit for the overall system performance was found by utilising a second-order high-pass filter (cueing algorithm), first-order low-pass filter (motion system) and fixed delay (time delays), with their respective roles following nomenclature of (Ref. 15). The Bode plot comparing this model to the experimental data is shown in the figure 7. This was obtained from analysing the velocity input and output, which gave best results overall. The biggest divergence from the experiment can be seen for the lowest frequencies, most likely due to not using the acceleration signal in this simplified formulation. This lack of a known formulation for the cueing algorithm and only partial characterisation, prevents directly adjusting its parameters for optimal control as suggested in (Refs. 5, 6).

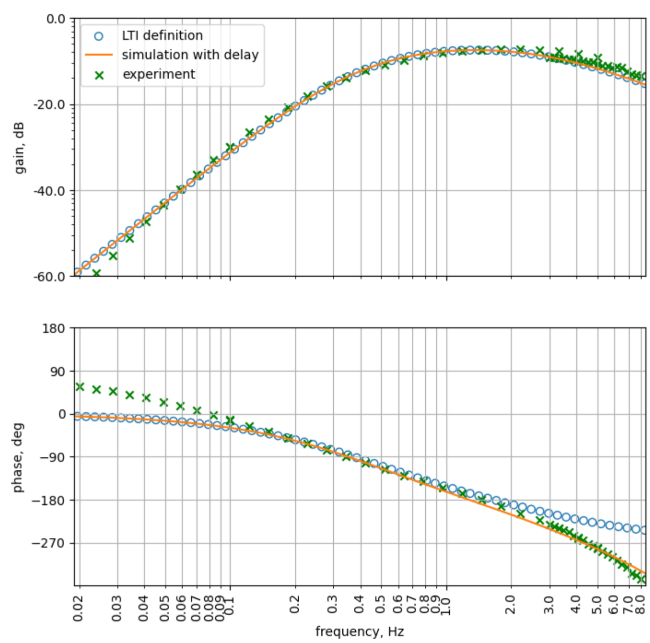

Figure 7. Final fit for heave axis

EVALUATION METHODS

Theoretical analysis

There is an objective evaluation method proposed by Advani-Hosman (Refs. 16, 17), which is based on the system's response in the frequency domain. One of its advantages is that, by design it does not reveal many details of the evaluated

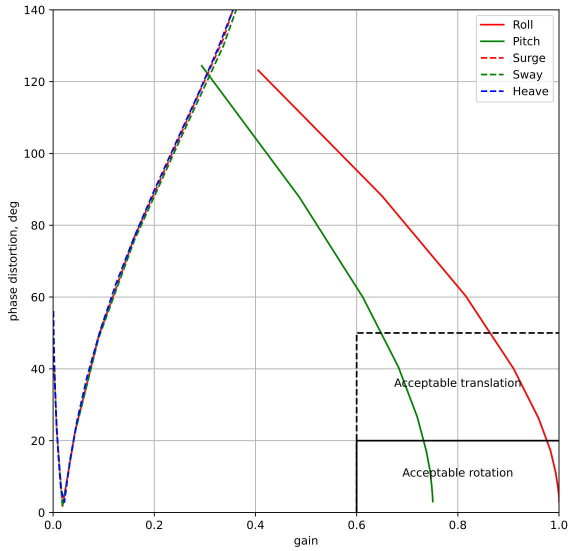

Figure 8. Plots for Advani-Hosman criterion

motion system, for protecting industrial intellectual property. This makes it a good fit for this use case of identifying a proprietary controller.

The roll and pitch response fit in the acceptable region up to 1.14 rad/s, but at higher frequencies, the phase lag is too large as seen in Figure 8. The yaw channel is not evaluated by the authors of this criterion. The values for translational cues measured with these experiments fall outside the acceptable range for this criterion; however they are comparable to some research simulators presented in the literature (Ref. 15).

Rating scales

The current approach found in the literature to tune the motion cuing system is mainly based on pilots' subjective feedback (Refs. 5,6) which, however may be imprecise and in any case highly affected by the experience level of pilots with VR headsets.

Since the objective of the simulated flight is a realistic reproduction of a human sensory experience, rating scales could be a tool that can be used to transform a subjective rating into a more rigorous scale. We advocate here the systematic use of the Simulation Fidelity Rating (SFR) scale (Ref. 18) as a method to characterise the simulator's overall fidelity.

This scale evaluates the overall immersive experience as perceived subjectively by the pilots. Such a scale would provide structure and standardisation to subjective testing. The scale has been designed to evaluate simulator utility in terms of fitness-for-purpose on a task-by-task basis, and it can be used to ensure that the simulator effectively replicates the sensory and cognitive demands of real flight.

The other tool considered for structuring the motion tuning is the Motion Fidelity Rating (MFR) scale (Ref. 19) with much the same objective as SFR introduced above, but focusing specifically on the response of the motion system.

Experiments

Three pilots were recruited to perform the evaluation of the simulator. One has reported discomfort from using the VR headset, and has not tested the described setup further. Among the remaining two, one is a holder of a private helicopter pilot license. The other is a fixed-wing sailplane pilot with only simulator experience of helicopters.

All participants were briefed about safe operating procedures, and had an emergency stop button available to them at all times. For each trial, there was an operator controlling the simulation, and a safety observer tasked only with supervising the motion system equipped with their own stop button. The sessions started with familiarisation with the simulated aircraft, first without movement. Motion cues were introduced initially at a lower amplitude, and scaled up after confirming no discomfort.

Both participants have rated the overall simulator to 7 on the SFR scale. Basic tasks from the ADS-33 standard were attainable, but with significant changes to piloting behaviour. The lack of ground contact in the simulation significantly affected the pilots' use of the collective control. Flying below the terrain level in the visualisation was very disorienting and uncomfortable, but it has happened multiple times at the start of a trial.

The pilots could hear the actuators moving, which was strengthened by the fully open cockpit structure. This feature, which is unique for VR, additionally caused the pilots to feel the apparent wind resulting from fast platform movements on their skin. This provided an additional cue not present in real flight, which communicated actual platform movements, thus worsening the immersion.

Even though the motion fidelity was lacking according to the criteria analysed in a previous section, all users evaluated it as a positive contribution to realism and performance (MFR ratings 4-6). More precise evaluation of the motion system itself was not obtained, as other issues were overshadowing the focus of the participants, none of whom are trained as test pilots.

ADJUSTMENTS

Based on the participant feedback, most changes were done to the flight model. Rotations of the linear model at high attitude angles were improved in the way described in the flight model section. Additionally, the initial implementation of the SAS system caused the controller to always attempt to return the aircraft to level flight, which caused wind-up of integral terms and migration of the cyclic lever trim position from centre. This was fixed by calculating the controller error relative to the tilt angle calculated from pilot input, resulting in a correct attitude-command-attitude-hold control.

The next reported issue was flying into the ground on take-off. Firstly, this was improved by displaying the trim position of the collective to the pilot in the way shown in figure 9. This allowed them to position the lever so the simulated flight starts from a trimmed hover condition. Finally, a simple ground contact model was implemented using the elastic stiffness and the damping coefficient of the landing gear. It was applied conditionally when the Z-coordinate of the simulated aircraft would go under the origin point, resulting in sensation of a flat ground. While this does not provide the level of detail necessary for landing and taxiing tasks, it is enough for take-off, where a feeling of the helicopter *getting light on its feet* is described by the pilots as the collective lever is moved from its bottom position upwards toward hover.

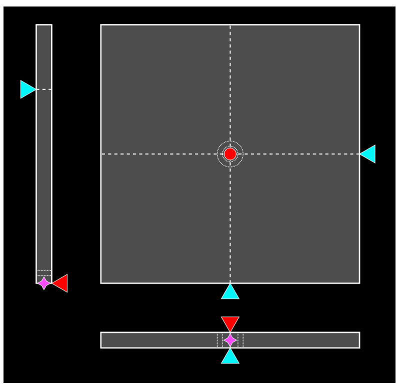

Figure 9. Controls view displayed in cockpit, with the trim positions indicated as cyan triangles

While the motion cueing algorithm embedded in the platform firmware was not available for tweaking, the software providing it with inputs has a feature of uniformly scaling the aircraft state between the simulated one and the trim condition. This was used for smoothly enabling the motion, gently introducing new users to the facility and as an overall gain filter before. Generally, the pilots preferred the cues to be scaled 75% or even 50% compared to direct simulation output. Note that this does not necessarily mean smaller displacement, as the high pass filters and excursion limits stay the same, but slower and less sudden movements.

There are many factors specific to the Virtual Reality setup that may explain this preference compared to the simulator, presumably tuned for a classical simulator cockpit with surround screens. An advantage of VR is apparent full surround by the generated visual imagery, which has been demonstrated to provide greater feeling of immersion (Ref. 20). This high-quality visual cue, may place less demand on the vestibular cues to create a good feeling of motion. On the other side, the specific headset used has a considerable weight[1], which was reported to cause strain on the head and neck when worn in the moving cockpit. Finally, the noise and wind described above were improved by introducing headphones that completely cover the ears, but remained a factor that was improved by lowering the gain.

[1]VARJO XR-3 weighs 980g, with ca. 590g mounted in front of the face

CONCLUDING REMARKS

Feedback from users placed importance on other aspects of the simulator than specifically details of the motion cue quality. This is confirmed by the regulatory requirements, as many of their aspects don't involve in-flight motion at all, but are there to communicate specific phenomena related to aerodynamics and ground contact that are not modelled presently (Ref. 14).

The typical VR motion system has a smaller cockpit than a full cockpit mockup, and thus proportionally smaller platform and actuators. This limits the range of possible motion cues of VR simulators, unlike this specific setup adapted to VR using a large motion platform. The preliminary findings suggest that a bigger motion cue travel may not always be preferred, as evidenced by preference for scaled-down inputs.

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REFERENCES

1. Gareth Padfield, Stefan van't Hoff, Linghai Lu, Mark White, and Giuseppe Quaranta. *Rotorcraft Certification by Simulation and Analysis: An Introduction to the Principles and Practices*. Springer, April 2025.

2. Marilena D Pavel, Michael Jump, Binh Dang-Vu, Pierangelo Masarati, Massimo Gennaretti, Achim Ionita, Larisa Zaichik, Hafid Smaili, Giuseppe Quaranta, and Deniz Yilmaz. Adverse rotorcraft pilot couplings—past, present and future challenges. *Progress in Aerospace Sciences*, 62:1–51, 2013.

3. Th. Brandt, J. Dichgans, and E. Koenig. Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental Brain Research*, 16(5):476–491, March 1973.

4. Don R. Gum. Modeling of the Human Force and Motion-Sensing Mechanics. Technical Report AFHRL-TR-72-54, Advanced Systems Division Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, OH, USA, 1973.

5. Peter R. Grant and Lloyd D. Reid. Motion Washout Filter Tuning: Rules and Requirements. *Journal of Aircraft*, 34(2):145–151, March 1997.

6. Robert J Telban and Frank M Cardullo. Motion Cueing Algorithm Development: Human-Centered Linear and Nonlinear Approaches. *New York*, 2005.

7. Marek S. Lukasiewicz. Modular architecture for reconfigurable simulation of helicopters: Online documentation. https://marsh-sim.github.io, last accessed 2025-07-16.

8. Gareth D Padfield. *Helicopter Flight Dynamics: Including a Treatment of Tiltrotor Aircraft*. John Wiley & Sons, 3rd edition edition, November 2018.

9. Andrés Marcos and Gary J. Balas. Development of Linear-Parameter-Varying Models for Aircraft. *Journal of Guidance, Control, and Dynamics*, 27(2):218–228, March 2004.

10. Juan Linietsky, Ariel Manzur, and Godot Engine contributors. Godot engine - free and open source 2d and 3d game engine. https://godotengine.org, 2007–2025.

11. Marek S. Lukasiewicz and Margaux Touzard. Visualisation for MARSH. https://git.lukasiewicz.tech/DAER/visualisation-marsh, last accessed 2025-07-16.

12. Aeronautical Design Standard Performance Specification Handling Qualities Requirements For Military Rotorcraft. Technical Report ADS-33E-PRF, United States Army Aviation And Missile Command, Aviation Engineering Directorate Redstone Arsenal, Alabama, March 2000.

13. CS-FSTD(H) Initial issue. https://www.easa.europa.eu/document-library/certification-specifications/cs-fstdh-initial-issue.

14. Manual of criteria for the quantification of flight simulators, 2003.

15. Sunjoo K. Advani, Ruud J.A.W. Hosman, and Mario Potter. Objective Motion Fidelity Qualification in Flight Training Simulators. In *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Hilton Head, South Carolina, August 2007. American Institute of Aeronautics and Astronautics.

16. Sunjoo K. Advani and Ruud J.A.W. Hosman. Revising Civil Simulator Standards - An Opportunity for Technological Pull. In *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Keystone, Colorado, August 2006. American Institute of Aeronautics and Astronautics.

17. Sunjoo K Advani and Ruud J.A.W. Hosman. Towards Standardising High-Fidelity Cost-Effective Motion Cueing in Flight Simulation. In *Cutting Costs in Flight Simulation. Balancing Quality and Capability*, Royal Aeronautical Society Conference, London, November 2006.

18. P. Perfect, E. Timson, M. D. White, G. D. Padfield, R. Erdos, and A. W. Gubbels. A rating scale for the subjective assessment of simulation fidelity. *The Aeronautical Journal*, 118(1206):953–974, August 2014.

19. S.J. Hodge, P. Perfect, G.D. Padfield, and M.D. White. Optimising the yaw motion cues available from a short stroke hexapod motion platform. *The Aeronautical Journal*, 119(1211):1–21, January 2015.

20. Katharina Margareta Theresa Pöhlmann, Gang Li, Mark Mcgill, Reuben Markoff, and Stephen Anthony Brewster. You spin me right round, baby, right round: Examining the impact of multi-sensory self-motion cues on motion sickness during a vr reading task. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, pages 1–16, 2023.