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Comparison of Visually Coupled System Performance in Helicopter Flight and Simulator Trials

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A study was conducted to compare and validate two visually coupled system (VCS) installations, one in a moving-base flight simulator and a second in a Bell 205 research helicopter. Standard low-level maneuvering tasks were used to examine changes in handling qualities. Pilots also assessed two levels of control augmentation: rate damped and translational rate command. The system handling qualities degraded whenever the VCS was used. Pilots reported that there were system deficiencies which increased their workload and prevented them from achieving desired task performance. The decline in handling qualities was attributed principally to the reduction in image quality while flying the helicopter with the VCS. The primary factors affecting performance included a reduction in image resolution, a reduction in the field of view, system latencies, and the limitations of the simulator mathematical model. Control augmentation improved the system handling qualities in the simulator and should be investigated further as an effective strategy for overcoming VCS limitations. The trends found in the simulator were comparable to those found in the helicopter and could be used to develop a VCS for military search and rescue applications.

Introduction

SEARCH and rescue (SAR) missions share common elements with the tactical helicopter environment: they often take place in inclement weather, poor visibility, or at night. It has been proposed that SAR helicopters follow the lead of attack helicopters and implement visually coupled systems (VCS) technology to improve mission effectiveness and safety.[1] A properly designed VCS can reduce pilot workload and extend aircraft capability in adverse conditions.

In the Apache helicopter pilots use a VCS called the Pilot Night Vision System (PNVS).[2] This system projects head-slaved imagery from a forward-looking infrared camera onto a monocular helmet-mounted display (HMD). The PNVS increased the tactical effectiveness of the Apache by improving the ability of pilots to carry out helicopter missions at night under low visibility conditions. The effectiveness of this system is revealed by the presence of similar visually coupled systems developed for the Tiger and Comanche helicopters.[2]

Despite the success of the PNVS, problems exist with visually coupled systems,[3] and little information is available that precisely describes the effects of VCS system parameters on pilot performance. For example, the relationship between the VCS video system time delay, and pilot performance is not well understood in all task contexts. Significant time delays in a visually coupled system degrade pilot performance and can possibly cause motion sickness. In addition, there are other VCS issues that are as yet unresolved, such as the effect of camera platform dynamics on pilot performance and the link between VCS image quality and control system augmentation.

A VCS system was installed on a Bell 205 research helicopter at the National Research Council of Canada (NRC) to be used in the investigation of the relationship between VCS system parameters and helicopter handling qualities and pilot performance. A second test HMD equipped facility was installed in a moving-base flight simulator at the University of Toronto Institute for Aerospace Studies (UTIAS). The simulator, which is less expensive to operate, safer, and capable of a higher throughput of experimental subjects, could be used to conduct preliminary broad-based investigations. The results of the simulator studies could then be used to reduce the number of experimental conditions to be tested on the helicopter VCS. However, to improve confidence in test results it would be necessary to validate and compare the handling qualities (HQ) of the simulator and helicopter visually coupled systems. This paper reports the results of a comparison of handling qualities ratings (HQR) obtained in the simulator to HQR obtained in the helicopter on a standard series of low-level maneuvering tasks with two different control systems.

Method

The VCS in the simulator and the helicopter were compared by two trained test pilots in a within subjects experimental design.[4] There were three variables considered in the direct comparison between helicopter and simulator: maneuvers, control systems (rate damped or translational rate command), and the test platform (helicopter or simulator). Table 1 summarizes the test parameters and includes one other test condition, the helicopter baseline (no helmet, rate damped control system). The pilots utilized a standardized test scenario based on a series of maneuvers adapted from ADS-33D.[5] Performance limitations of the Bell 205 helicopter necessitated maneuver performance criteria changes to prevent equipment damage. Maneuver criteria were further adjusted to obtain borderline level 1 or better handling qualities ratings for the baseline helicopter in a good visual environment (GVE). Good baseline HQ were deemed necessary to prevent a ceiling effect on performance and ensure that changes in handling qualities caused by the VCS limitations could be measured and attributed to experimental manipulation.

A more detailed description of the maneuvers and criteria changes employed in the assessment of helicopter HQ investigation is contained in Swail et al.[6] The maneuvers represented typical low-level aggressive and precision maneuvers designed to test the system capabilities under a variety of pilot control input strategies and workload conditions. The maneuvers included two precision tasks, the hover and landing; two dynamic large single-axis control input tasks,

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Table 1 Experimental conditions

Platform	Condition title	HMD	Control system	Performance criteria
Helicopter	Helicopter baseline RD	Not used	Rate damped	Good visual environment
Helicopter	Helicopter RD	Used	Rate damped	Degraded visual environment
Helicopter	Helicopter TRC	Used	Translational rate command	Degraded visual environment
Simulator	Simulator RD	Used	Rate damped	Degraded visual environment
Simulator	Simulator TRC	Used	Translational rate command	Degraded visual environment

Table 2 Subject pilot qualifications

Pilot	Age	Total hours	Helicopter hours	NVG/HMD hours
1	35	2850	2600	20
2	35	4100	2900	10

the sidestep and quickstop; and a multiaxis control input task, the pirouette. Maneuvers were blocked by control augmentation type, and pilots performed a counterbalanced series of maneuvers within each control response block.

Pilots performed the maneuvers with two levels of control augmentation: rate damped (RD) and translational rate command (TRC). The RD control response type provides a rotational rate proportional to the stick or pedal displacement and is the preferred system for aggressive maneuvering in good visual conditions. Interaxis decoupling was used in both the helicopter and simulator RD control augmentation schemes; however, height hold was available only in the TRC condition in both systems, whereas heading hold was available only in the simulator. The TRC control response type provides a horizontal velocity proportional to the cyclic stick displacement. Based on the information available in ADS-33D,[5] it is the preferred system for use in extremely degraded visual environments (DVE) equivalent to a useable cue environment (UCE) rating of UCE 3. TRC was chosen to evaluate a range of control augmentation schemes given the possibility of encountering poor performance while using the HMD systems.

A series of highway traffic cones, laid out in a grass field near the NRC hangar, located beside the Ottawa International Airport, marked the performance criterion limits for the maneuvers. The maneuvers in the helicopter were always performed in good visual meteorological conditions (VMC) with winds less than 15 kn. UTIAS personnel duplicated the field layout in the simulator terrain database. In the UTIAS simulator the maneuvers were flown in simulated VMC with a turbulence model that reflected the light turbulence encountered during the helicopter tests.

During the evaluation, the pilots practiced each maneuver at least twice (in both the helicopter and the simulator) before ratings were gathered. HQ criteria were evaluated using Cooper-Harper HQR[7] and a questionnaire. In addition, extensive pilot debrief sessions were used to elicit comments regarding helicopter and simulator performance.

Two qualified ex-military test pilots participated in the study. They had normal visual acuity and no known visual deficits. The subject pilot qualifications are listed in Table 2. Both pilots had had a small amount of exposure to night vision goggle (NVG) or HMD systems. They received 4–10 hours of training on both the helicopter and simulator systems to augment their limited experience and achieve a stable level of performance using the HMD.

Apparatus

Detailed descriptions of the experimental apparatus are given in Swail et al.[6] for the helicopter VCS and in Reid et al.[8] for the simulator installation. A short description follows for systems relevant to this study. In the helicopter the pilot's head movements were determined using a mechanical head tracker. A gimbaled camera platform (see Fig. 1) mounted on the helicopter roof duplicated the pilot's rotational head movements. Imagery from two NTSC video cameras (on the camera platform) was transmitted to the HMD projection system and relayed via coherent fiber-optic cables to the pilot's head-mounted display optics. The display imagery was conformal with the real world referenced to the camera viewpoint. A system transfer function relating lateral cyclic force to aircraft roll rate for the NRC Bell 205 helicopter is shown in Fig. 2. Helicopter control laws were based on data from Heffley et al.,[9] and details for the hover situation are covered in Table 3. Table 4 specifies the camera platform characteristics.

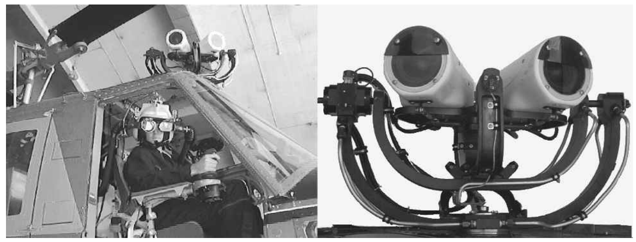

Fig. 1 NRC HMD installation and camera platform.

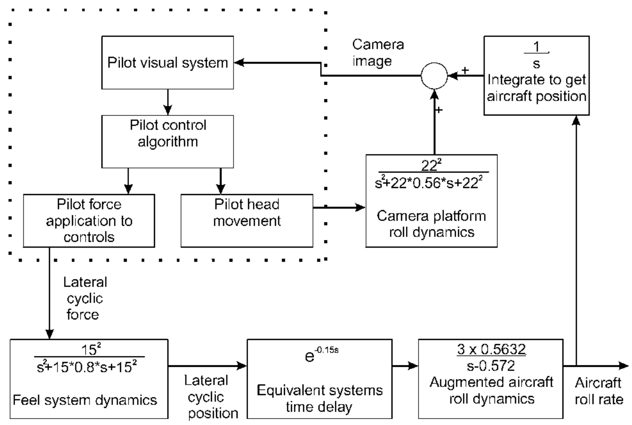

Fig. 2 Transfer function for helicopter roll during a hover.

The simulator system uses a similar display medium: a fiber-optic HMD. However, a magnetic head tracker measured head movements, and a computer image generator (IG) replaced the cameras. The IG used the head position and orientation information to generate an image from a database, which was based on the NRC test field. The IG viewpoint was located at the same position as the actual helicopter cameras (i.e., on top of the roof above the pilot's head). The image was rendered by the HMD projection system and displayed on the helmet optics. Both HMD systems were similar color displays with the key differences between the two systems presented in Table 5. The UTIAS Flight Research Simulator is shown in Fig. 3. The helicopter model was matched in the simulator using a comparison of the time history response to control inputs, subjective evaluations, and an assessment of attitude and control positions in trim conditions. The model is based on a series of nonlinear differential equations. Transfer functions are not available for the simulator.

The nonlinear helicopter model employed in the simulator is based on the ARMCOP[10] (ARMy heliCOPter) generic code developed at NASA Ames Research Center and modified for the University of Toronto as outlined in Reid.[11] This code employs a rotor disc model with underlying parameters selected to represent the Bell 205. Evaluation trials with this parameter set indicated that the basic airframe reasonably represented the NRC helicopter. An automatic flight control system (AFCS) was then implemented on the simulated helicopter, which provided a number of control response types, including rate damped and translational rate command.[4,8] The AFCS parameters were selected to provide good handling qualities.

Table 3 Helicopter system characteristics

Aircraft control	Feel system dynamics,[a,b] $\frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$	Aircraft response axis	Augmented aircraft response,[c,d,e] $\frac{a\times b}{s-c}$
Lateral cyclic	Spring gradient = 0.5 lb/in., $\omega_n = 23$, $\zeta = 3.5$	Roll	$\frac{3\times 0.5632}{s-5.0}$
Longitudinal cyclic	Spring gradient = 0.5 lb/in., $\omega_n = 23$, $\zeta = 4.7$	Pitch	$\frac{1.91\times(-0.1691)}{s-1.8}$
Pedals	Spring gradient = 1.5 lb/in., $\omega_n = 12$, $\zeta = 16$	Yaw	$\frac{1.55\times(-1.1963)}{s-2.5}$
Collective	4–6 lb of friction	Vertical velocity	$\frac{-9.7745}{s-0.385}$

[a] ω_n is the natural frequency in radians/s.
[b] ζ is the damping constant (dimensionless).
[c] a is the sensitivity gain on the control input (in./in.).
[d] b is the control power (roll, pitch, and yaw in rads/s^2/in., heave ft/s^2/in.).
[e] c is the aircraft damping s^{-1}.

Table 4 Camera platform response characteristics

Axis	Camera platform angular response to a head rotation,[a,b] $\frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$
Roll	$\omega_n = 22$, $\zeta = 0.56$
Pitch	$\omega_n = 32$, $\zeta = 1.41$
Yaw	$\omega_n = 35$, $\zeta = 1.00$

[a] ω_n is the natural frequency in radians/s.
[b] ζ is the damping constant (dimensionless).

Fig. 3 UTIAS flight simulator.

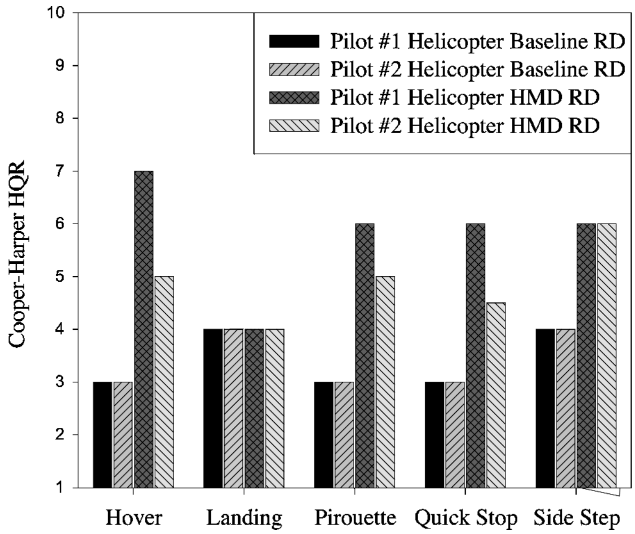

Fig. 4 Helicopter handling qualities changes caused by the visually coupled system.

This resulted in flight characteristics with the AFCS turned on that approximated those of the NRC helicopter in the RD mode and exceeded them in the TRC mode (for both aggressive maneuvers and flight in ground effect). The intent was not to duplicate the helicopter exactly, but to develop a helicopter simulator that could test VCS concepts and predict trends likely to be found in the NRC helicopter caused by variations in the VCS configuration.

Results

A clear-hood condition in the NRC helicopter was used as a baseline. During the clear-hood conditions (VFR), the pilots did not use any aids to fly the aircraft nor had they any restrictions on their vision. The pilots were able to perform the maneuvers to the GVE desired criteria in the clear-hood condition as shown in Fig. 4 (i.e., they achieved borderline level 1/level 2 HQR). However, as soon as the VCS was used, HQR deteriorated to level 2 using the DVE maneuver criteria.

Close agreement was obtained among HQR of the helicopter and simulator in the rate damped control configuration as shown in Fig. 5. Handling qualities ratings reflect both system performance and pilot workload. They were within two Cooper–Harper HQR points of each other at all times, and 90% of the time they were within 1.5 Cooper–Harper HQR points. The simulator was rated the same as the helicopter in 4 of the 10 cases, better by one HQR in 4 of the 10 cases, and better by 1.5 HQR in 2 of the 10 cases (the sidestep maneuver). It is clear that the simulator handling qualities were always equivalent to or better than the helicopter.

When the control augmentation schemes were properly implemented, system handling qualities improved as shown in Fig. 5. In general, the TRC control system was rated the same as or better than the RD control system. The simulator TRC condition was primarily rated as a level 1 aircraft (9 of 10 ratings). However, pilot 2 did rate the helicopter TRC system worse than the helicopter RD system in two conditions. The implementation of TRC in the NRC helicopter suffered from a number of problems, which led to poor ratings.

There are maneuver-dependent differences in the ratings for both platforms. The landing maneuver received the lowest HQR (i.e., lowest workload and best performance) in both the simulator and the helicopter, whereas the hover generally received high HQR in both devices.

Discussion

The results of these tests were obtained from observations by only two test pilots. Thus the results have limited statistical power,

Table 5 Comparison of helicopter and simulator VCS characteristics

Equipment	UTIAS simulator	NRC 205 helicopter
Headtracker	Polhemus magnetic	Mechanical
FOV		
monocular	46° H × 36° V	62.5° × 40°
overlap	21°	25°
total	71° × 36°	100° × 40°
Image source	Max vue enhanced B image generator	NTSC video cameras on a gimbaled platform
Resolution	1180 × 1056	754 × 485
Vertical resolution	4.7 arc min/pixel pair	10.0 arc min/pixel pair
Motion cuing	six-degree-of-freedom motion base	Actual 205 dynamics
Helmet weight relief	Used	Not available
Helmet liner	Inflatable	Inflatable or custom foam
Time delay in response to head movement	Near zero with lead compensation	Variable, depending on axis pitch = 150 ms, roll = 35ms, yaw = 105 ms

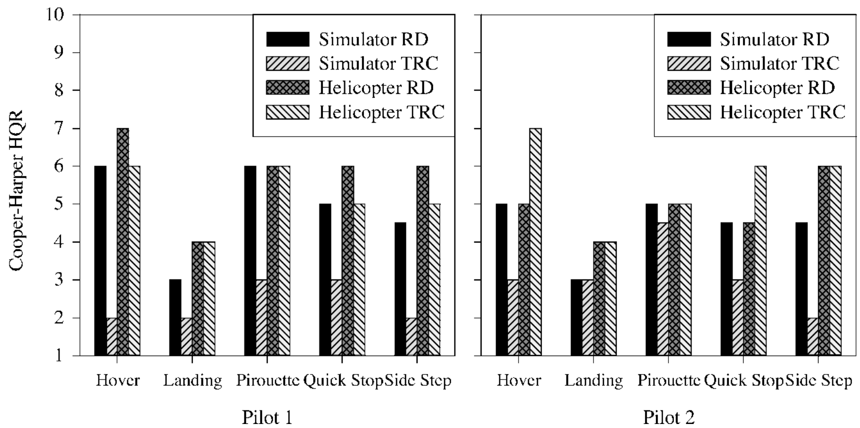

Fig. 5 Comparison of helicopter and simulator handling qualities ratings.

but we believe they accurately illustrate trends in handling qualities changes because of the use of HMD systems. The pilots had some, but not extensive, NVG and HMD training. However, they did receive extensive training on the HMD to achieve a stable level of performance prior to the start of the experimental evaluation. The results of these tests should be applicable to other visually coupled systems.

The baseline helicopter with a rate damped control system was a borderline level 1/level 2 aircraft, where desired maneuver criteria (GVE) could always be met. Whenever the HMD was used on the helicopter, the handling qualities degraded to a solid level 2 (DVE criteria). The simulator was also rated as a level 2 aircraft (DVE criteria) using the rate-damped control scheme. The decline in handling qualities, from level 1 to level 2 DVE, can be attributed to the use of the HMD, and a subsequent reduction in image quality and change in visual system dynamics. Because the HMD affects the visual environment that the pilot sees, it is reasonable to explain the degradation in performance by a change in the visual cues that the pilots used to control the aircraft.

Some of the primary changes in the HMD visual system from normal human vision are a decrease in resolution, image contrast and field of view (FOV), and the introduction of visual system dynamics and latencies (i.e., time delays in the image processing, camera update rates, and camera platform movement time delays). These changes likely affect HQ when switching between the baseline helicopter operated without unique visual systems and the helicopter equipped with an HMD. Differences among the handling qualities obtained using the simulator HMD and the helicopter HMD can also be explained by these factors. However, there is one additional factor that affects handling qualities differentially in the simulator and helicopter: the simulator mathematical model used to represent the flight dynamics of the helicopter. The following paragraphs describe some of the VCS factors that affect performance in more detail.

Field of View

Previous studies have found that FOV restrictions affect pilot performance, reducing effectiveness, and maneuver aggressiveness. Previous tests[12] have shown that the combination of FOV and binocular overlap used in this experiment (see Table 5) decreases level 1 HQR to borderline level 2 HQR in good visual environments. It has been shown that reduced FOV affects the perception of height, produces a tunneling of the visual field and a loss of peripheral vision, and creates a "loss of general situational awareness." Small FOVs prevent quick and accurate capture of visual cues for attitude, translation and position, as well as quick and accurate readings of cockpit instruments. Pilots have been known to compensate for a reduced visual field by changing the frequency, amplitude, and pattern of head movements.

Resolution

The human eye with normal vision can distinguish details in the neighborhood of 1 arc min in size for 20:20 vision. This performance is better than the best theoretical capability of the NRC display with a resolution of 5 arc min per pixel and a corresponding best acuity of 20:100. The poor NRC HMD resolution was noted as one of the main factors affecting performance in the helicopter. Pilot 1 was tested on a standard Snellen Eye chart displayed on the HMD. He had a visual acuity of $\frac{20}{120}$ in the left channel and $\frac{20}{200}$ (legally blind) in the right channel, as a result of incorrect collimation of the right eye helmet optics. The collimation problems were fixed before pilot 2 began the test program. He tested with an improved acuity of $\frac{20}{120}$ in each eye. Because of the poor acuity, pilots reported difficulty in obtaining the cues necessary to complete a task. For example, when the helicopter was situated at the start of the quickstop course they were unable to see the cones marking the end of the quickstop course, which were easily visible to the naked eye. Consequently, the pilots had a reduced capability to both plan their flight path along the course and use predictive control techniques.

Psychophysical tests of acuity are more difficult to conduct in the simulator, but an approximate Snellen equivalent of 20:47 was calculated given the 2.35 arc min/pixel vertical density of the display. Subjective reports from pilots and investigators confirm that simulator HMD acuity was much better than NRC HMD acuity. It is believed that improved resolution will allow the pilot to better detect motion of small image elements resulting in better control performance.

System Latencies

System latencies increase pilot workload and reduce performance because they affect the closed-loop stability of the pilot-helicopter system, thereby generally decreasing the ability of the pilots to control the system. The visual system latencies of the two fiber-optic HMD displays used in this study are very low and on the order of one interlaced field, typically less than 16 ms. However, an examination of the systems reveals other delay sources. For example, the image generation time in the simulator is in the order of 70 ms in response to aircraft movements and close to zero in response to pilot head movements. In comparison, one can see from the helicopter transfer function that there are delays in the camera platform and in the control system. The helicopter camera platform time delay is larger than the simulator response to head movements: pitch axis equivalent time delay is approximately 150 ms, roll axis equivalent time delay is 35 ms, and yaw axis equivalent time delay is 105 ms. Furthermore, Hui[13] has shown the helicopter control system has an equivalent systems delay of approximately 150 ms that varies slightly for the lateral cyclic, longitudinal cyclic, collective, and pedals.

Previous research has shown that both control and image lags in this region can interfere with the pilot's ability to control an aircraft. Wildzunas, et al.[14] summarize a number of studies that show time delay in the visual system can reduce pilot performance and change pilot control behavior. In their review the three studies on rotorcraft simulation show reductions in performance at time delays of 63, 89, and 132 ms. These delays are comparable to the delays encountered in the helicopter VCS and simulator.

There may be further effects on the pilot aside from a reduction in performance caused by decreased gain and phase margins. Reason and Brand[15] postulate possible disorientation when a delayed image introduces mismatches between the visual and vestibular experiences of orientation. The physiological symptoms may can an effect on the pilots capacity to adjust to increasing workload, and this avenue is worthy of further investigation.

It is important to draw a distinction in the possible locations of time delay. Although image lags or visual delays are present the visual feedback loop (e.g., camera platform dynamics in Fig. 2), control system delays are between the control effector and the system response (e.g., equivalent systems time delay in Fig. 2). Delays in the two different locations can have different effects on pilot-in-the-loop performance. It has also been shown that the effect of control time delay is highly task dependent. Smith and Bailey[16] found that pitch pilot-induced-oscillation tendencies became evident only when the pilots performed a precision landing task that placed high control demands on the pitch axis.

Further research into the effects of visual system time delay on pilot control performance is warranted. The results of this initial validation suggest that the helicopter VCS system and simulator HMD are uniquely capable of investigating this domain.

Control Augmentation and the Helicopter Model

Control system augmentation is a common practice for reducing pilot workload and improving performance. Augmenting the simulator control system by implementing TRC improved the handling qualities to level 1 as predicted from development work leading up to ADS-33D. Unfortunately, the same improvements were not seen in the helicopter because of poorer implementation. The helicopter sensor system suffered from dropouts and drifts in the Doppler radar and global positioning system. These dropouts and drifts reduced the effectiveness of the helicopter TRC system, and pilots could not effectively use it. In the simulator the sensors behaved more precisely, resulting in the expected improvement in system performance and a consistently large difference in pilot ratings between the RD system and the TRC system.

The helicopter model employed in the simulator was not intended to duplicate the NRC Bell 205 exactly, but to develop a helicopter simulator that could test VCS concepts and predict trends likely to be found in the NRC Bell 205 caused by variations in the VCS configuration. HQRs from the pirouette using a rate-damped control system were similar in both the helicopter and simulator. Similar HQRs were also obtained for the pirouette and hover from both platforms.

However, there were a few situations in which simulator HQRs did not accurately reflect HQRs obtained in the helicopter. For example, pilots always rated the quickstop as easier in the simulator than in the helicopter. They stated that one of the primary reasons that the simulator was easier to fly was that the simulator model did not possess all of the idiosyncrasies of a real helicopter. While in the simulator, pilots had far more power margin available to complete the maneuver, which did not accurately reflect the real world situation. Pilot monitoring of the power margin or torque margin is a major workload driver in the performance of the quickstop.

In a similar vein the lower pilot ratings for the sidestep in the simulator can be explained by the lower workload required to perform the task in the simulator. The simulator incorporates an idealized tail rotor model that does not account for vortex shedding during lateral translational flight. Vortex shedding causes the helicopter to become unstable in yaw. Yaw instability requires a certain amount of pilot workload to correct, which drives the Cooper–Harper ratings up.

Conclusions

The tests carried out in the helicopter and simulator were successful. Evaluations performed in the NRC Bell 205 indicated that the use of the helmet-mounted display degraded the handling qualities ratings to solid level 2 for the degraded visual environment criteria from the borderline level 1 good visual environment values found for the clear-hood baseline configuration. This was consistent with past experience. System handling qualities ratings based on the simulator visually coupled system were similar to those found during flight test of the Bell 205 helicopter visually coupled system. Control augmentation appeared to be an effective method of improving handling qualities when using a visually coupled system. The better ratings found in the simulator for the translational rate command control response type were expected, whereas the inconsistent results obtained with the helicopter were attributed to an ineffective implementation in the helicopter. The evaluation pilots felt that handling qualities trends found in the simulator were directly applicable to the National Research Council of Canada's Bell 205 helicopter visually coupled system, and the trends could be used to develop a fielded system for search and rescue applications. Further analysis is required to examine workload reduction in visually coupled systems through control augmentation and to clarify the differential effects of time and visual delays on pilot performance.

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