ROTORCRAFT FLIGHT DYNAMICS AND CONTROLS RESEARCH AT NASA

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In recent years, NASA has invested in key activities in the areas of flight controls, handling qualities and operations of rotorcraft for civilian applications. More specifically, the flight dynamics and control discipline has focused on analyzing the unique flight control and handling qualities challenges of large rotary wing vehicles anticipated for future passenger service, and examining the effect of control system augmentation on handling qualities for current civilian helicopters in order to improve safety and reduce accident rates. This paper highlights two recent research efforts in these areas. The first is an examination of flight control and handling qualities aspects of large rotorcraft. A series of experiments were performed in the large-motion Vertical Motion Simulator at NASA Ames Research Center to quantify the effects of vehicle size on flight control requirements and piloted handling qualities. These experiments used a large tilt-rotor concept (~100 passengers) to also investigate the control augmentation required to obtain Level 1 handling qualities for a vehicle of this size. The second is an examination of the effect of control system augmentation on handling qualities for current civil rotorcraft, like those currently used for Emergency Medical Service type operations. Many current civilian helicopters have rate response type control systems and little or no control system augmentation, although current technologies allow helicopters to be fitted with stability augmentation systems, either as standard equipment or aftermarket options. A simulation experiment was conducted in the Vertical Motion Simulator to quantify the effects of advanced control modes available with a partial authority stability augmentation system on task performance and handling qualities in both good and degraded visual conditions. In addition to providing an overview of the rotary wing flight dynamics and controls research at NASA, this paper will provide an overview of these two research activities along with key results and conclusions.

Introduction

Flight dynamics and control for rotorcraft pose unique challenges due to the inherent instabilities of the flight vehicle, the aerodynamic and mechanical complexity of the system, and the operational environment, which is often obstacle-rich with poor visibility at low altitude. As new technologies are integrated into existing rotorcraft configurations and designs for future advanced rotorcraft are contemplated, it is essential that control of flight and the capabilities of the pilot be integrated in the design process from the beginning. With these new technologies, configurations and capabilities, many new challenges are presenting themselves in the rotorcraft flight dynamics and control discipline. New heavy lift rotorcraft concepts are being proposed for development. New active rotor and flow control systems and devices are being developed and tested in the laboratory, in large-scale wind tunnels, and in flight. New variable-geometry and variable-speed rotor configurations are being studied for their performance potential. New strategies for flight-trajectory planning are being developed to provide for low-noise flight profiles and simultaneous non-interfering flight in the airspace. New human-system integration architectures, seeking to define an optimum balance between man and machine for aircraft control, are also being explored. All of these emerging vehicle design and operational trends will demand that the flight dynamics and control discipline, and its associated tools, techniques, and technologies, evolve to meet these challenges.

The vision for rotorcraft research in NASA has two main focuses: first is to provide a long term vision for vertical lift vehicles, particularly for passenger transportation to relieve congestion and increase throughput of future air transport systems; and, second is focused on increasing performance, efficiency and safety, and decreasing noise and emissions of current rotary wing vehicles. To be consistent with this vision, rotorcraft flight dynamics and control research within NASA has focused on analyzing the unique flight control and handling qualities challenges of large rotary wing vehicles anticipated for future passenger service, and examining the effect of control system augmentation on handling qualities for current civilian helicopters in order to improve safety and reduce accident rates.

This paper describes two recent flight dynamics and controls research efforts to address the vision of NASA rotary wing research goals. The first is an examination of flight control and handling qualities aspects of large rotorcraft. Large rotorcraft pose some unique challenges for flight control and operations due to their large mass and inertias resulting in low bandwidth vehicle response,

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and large distance from the center of gravity to the pilot station in the front and passengers at the back. A series of experiments were performed in the large-motion Vertical Motion Simulator (VMS) at NASA Ames Research Center to quantify the effects of vehicle size on flight control requirements and piloted handling qualities. These experiments used a large tilt-rotor concept (~100 passengers) to also investigate the control augmentation required to obtain Level 1 handling qualities for a vehicle of this size. The second is an examination of the effect of control system augmentation on handling qualities for current civil rotorcraft, like those currently used for Emergency Medical Service type operations. Many current civilian helicopters have rate response type control systems and little or no control system augmentation. Current technologies allow helicopters to be fitted with stability augmentation systems, either as standard equipment or aftermarket options, to make the helicopter easier to fly, particularly at night and in degraded visual environments. A separate experiment was conducted in the VMS to quantify the effects of advanced control modes available with a partial authority stability augmentation system on task performance and handling qualities in both good and degraded visual conditions.

This paper first describes the Cooper-Harper handling qualities rating scale (Ref. 1) that are used to evaluate human pilot workload and achievable precision for a particular task, vehicle, and control augmentation. Then the Vertical Motion Simulator at NASA Ames Research Center is described that has been used to generate all of the piloted simulation handling qualities results presented in this paper. The paper then describes two recent flight dynamics and control research efforts, including an overview and objectives, approach, and some key results and conclusions from this work.

Handling Qualities

Although modern aircraft design automates much of the traditional piloting role, the ability to fly with a human controlling the aircraft remains a primary means of operation for less-augmented aircraft, a means of dealing with unexpected or constantly changing missions (such as for military aircraft), or as a reversion to human control upon failure of parts of the automated system. As such, design for human control remains an important metric for the aircraft-control designer. Evaluation of piloted handling qualities remains a critical metric for satisfactory aircraft-control design. As defined by the seminal work by Cooper and Harper (Ref. 1) on the topic, Handling Qualities is defined as "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role."

The Cooper-Harper Handling Qualities Rating (HQR) scale continues to be a key differentiator in evaluating handling qualities of different vehicle dynamics, control system response types and architectures, and form the basis of the HQR results presented in this paper. Pilot assessment and assignment of a Cooper-Harper HQR requires an evaluation task and performance (precision) metrics that a pilot uses to arrive at a numerical rating. The rating is arrived at by working through the dichotomous decision tree involving both task performance and pilot workload, as illustrated in Figure 1. Careful description of the task and required performance with evaluation pilots has generally produced consistent evaluation results, augmented by pilot standardization through the auspices of various flight-test schools.

Core concepts of the HQR are the definitions of desired or acceptable task performance and a discussion of satisfactory or adequate workload. With these parameters defined, a pilot can work through the decision blocks on the left side of Figure 1. These decisions produce three bands of handling-qualities assessments plus the totally unacceptable uncontrollable result. The three bands are often referred to in association with handling-qualities "levels" which roughly translate into:

- Level 1: Satisfactory without improvement
- Level 2: Adequate performance, but improvement required
- Level 3: Unacceptable performance and/or workload

The goal of a controls designer is to achieve Level-1 handling qualities. A design with Level-2 handling qualities may be accepted for some adverse tasks (such as extreme winds and turbulence) or for recovery from a major system failure (such as an engine failure).

NASA Ames Vertical Motion Simulator

The Vertical Motion Simulator (VMS) is located at NASA Ames Research Center and has been a key simulation facility for helicopter and rotary wing vehicle flight control and handling qualities research for over 30 years (Ref. 2). The VMS combines a high-fidelity simulation capability with adaptable simulation environment that allows the simulator to be customized to a wide variety of human-in-the-loop research applications. The distinctive feature of the VMS is its large amplitude, high-fidelity motion capability. The high level of simulation fidelity is achieved by combining this motion fidelity with excellent visual and cockpit-interface fidelities. An interchangeable cab arrangement allows different crew vehicle interfaces and vehicle types to be evaluated, allowing fast turnaround times between

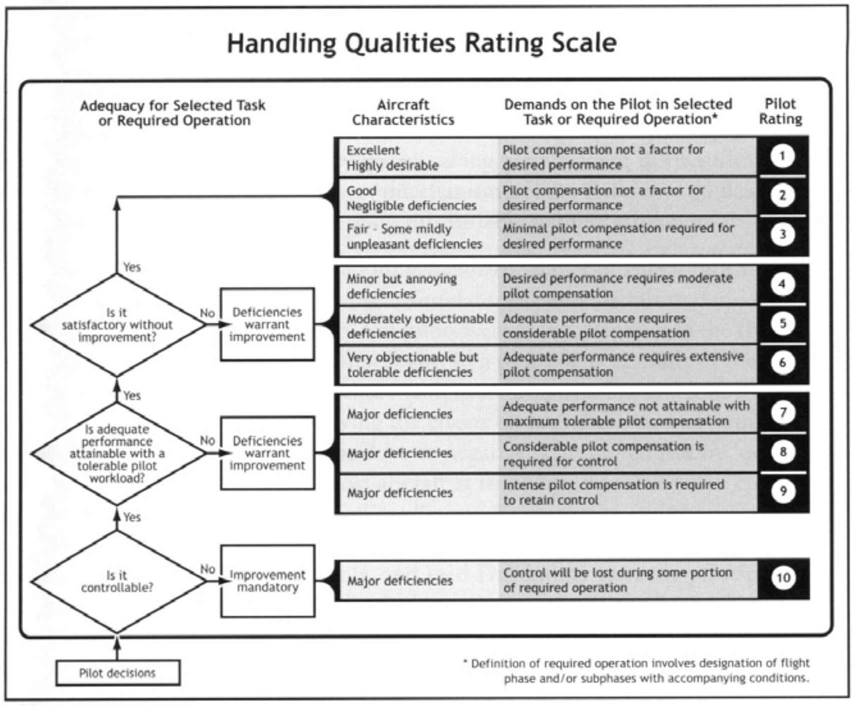


Figure 1. Cooper-Harper handling qualities rating scale.

Figure 2. NASA-Ames Vertical Motion Simulator (VMS).

Figure 3. NASA-Ames Vertical Motion Simulator cockpit and display layout.

simulation projects. The VMS motion system is a six-degree-of-freedom combined electromechanical/ electrohydraulic servo system, shown in Figure 2. It is located in and partially supported by a specially constructed 120-ft tower. The motion platform consists of a 40-ft-long beam that travels ±30 ft vertically. On top of the beam is a carriage that traverses the 40-ft length of the beam. A sled sits atop the carriage, providing the ±4 ft of travel in a third translational degree of freedom. A conically shaped structure is mounted on the sled and rotates about the vertical axis, providing yaw motion. A two-axis gimbal allows pitch and roll motion.

The VMS allows the cockpit to be tailored in terms of the flight controls, flight instruments and displays, seats, and out-the-window visuals to the specific research application. For rotary wing vehicle research, the cab provides the pilot with a 205-degree field of view, as well as a chin window, as shown in Figure 3.

Large Rotorcraft Handling Qualities

From 2008 to 2011, NASA and the U.S. Army Aeroflightdynamics Directorate (AFDD) conducted 4 simulation experiments in the VMS to investigate flight control system requirements and handling qualities aspects of very large rotorcraft. The details of these experiments are provided in References 3-8 and a summary, including the motivation, approach, and key results and conclusions, is presented in this section.

Introduction

NASA has delineated the Large Civil Tiltrotor (LCTR) concept design as the heavy-lift, high-speed rotorcraft configuration with the best potential to meet the technology goals associated with a notional civil mission of operating short-haul regional routes and for substantial impact on the air transportation system (Ref. 9). A series of system studies (Refs. 10–15) have shown that having a vertical capability at one or both ends of a 300-600 nautical mile mission increases airport capacity and that large, advanced technology tiltrotors consistently outpace other configurations in the ability to meet these transportation missions. The latest design evolution of the LCTR, the Large Civil Tiltrotor, 2nd generation (LCTR2) configuration, is sized to be representative of equivalent regional jets and turboprops (Ref. 9). Designed to carry approximately 90 passengers, over a range of at least 1000 nautical miles, at a cruise speed of 300 knots, this later LCTR configuration weighs around 100,000 lb, has a 107 ft wingspan, and two tilting nacelles supporting 65 ft diameter rotors. The general aircraft dimensions are shown in Figure 4.

Large rotorcraft, such as these LCTR concepts, pose some unique challenges for flight control and operations due to their large mass and inertias resulting in low bandwidth vehicle response, and large distance from the center of gravity to the pilot station in the front and passengers at the back. Advanced technologies will be required to give tiltrotors cost and operational parity with configurations already in use. Ultimately, however, the handling qualities requirements must accommodate the envisaged role, which will require precise maneuvering in cluttered terminal area environments, all weather operations and operational safety standards comparable or superior to that of current fixed-wing commercial operations. In line with these mission demands, key among quantitative requirements are metrics associated with the attitude response to piloted stick inputs such as bandwidth, phase delay, short-term response damping, and quickness. In addition to providing satisfactory response to piloted inputs, the flight control system must also reject responses due to disturbances and provide for an inherently stable

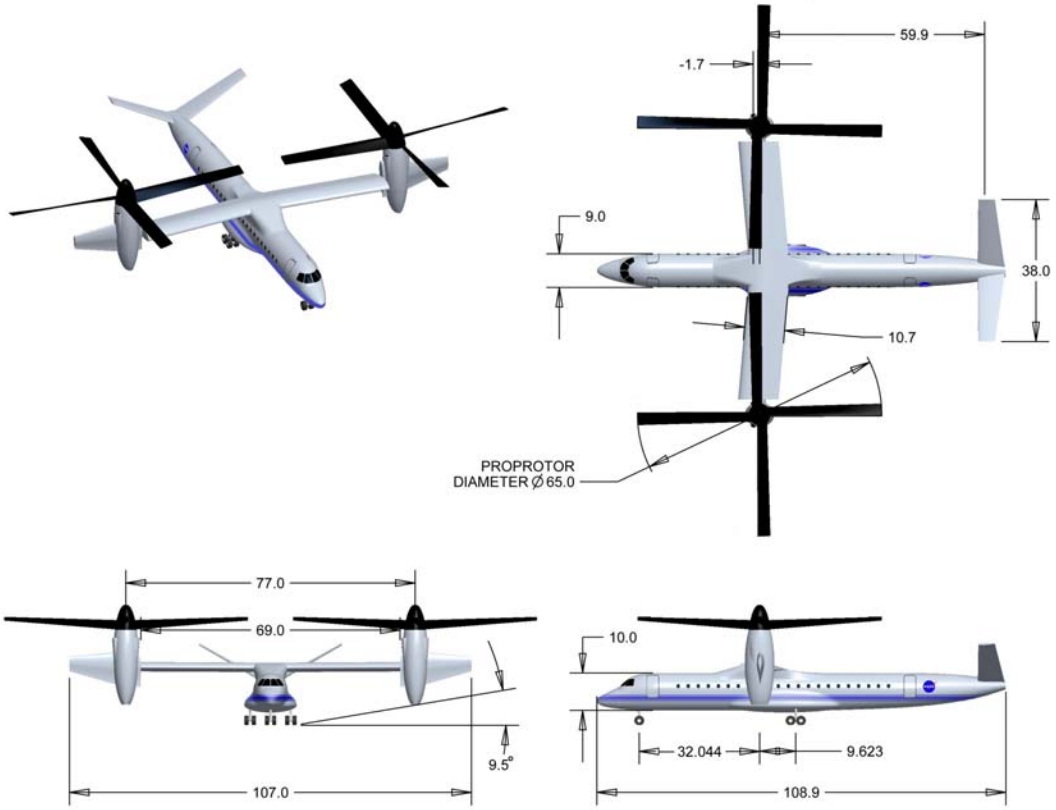


Figure 4. The NASA Large Civil Tiltrotor, LCTR2 baseline version (dimensions in feet).

platform with satisfactory margins to address both variations in flight conditions and uncertainties in dynamic response.

Objective

The overarching objective of this study was to quantify the fundamental relationships between rotorcraft size (both weight and dimension) and handling qualities in the critical hover and low speed flight regime. More specifically, this research intends to make the link between gross weight and handling qualities; as well as the connection between longitudinal pilot offset from the center of gravity and the allowable attitude changes in the control response type. As a second objective, the study explored the use of advanced control modes that take advantage of the unique characteristics of tilt-rotors to improve handling qualities.

Approach

A series of experiments were performed in the VMS to quantify the effects of vehicle size on flight control requirements and piloted handling qualities in hover and low speed. The first study pursued the piloted evaluation of various families of disturbance rejection bandwidth and stability margins on rotorcraft of varying gross weight. The rotorcraft models considered in this experiment included a utility class sized aircraft similar to a UH-60, a medium-lift cargo class CH-53K sized aircraft, and a heavy-lift large civil tiltrotor. Further experiments focused exclusively on the LCTR2 to investigate the level of control augmentation required to obtain Level 1 handling qualities for a vehicle of this size. To investigate the effect of pilot station location relative to the aircraft center of gravity, and the attitude response-type requirements on the handling qualities of this type of aircraft, the pilot station offset was varied to 10, 20, 30 and 40 feet, while keeping the LCTR aircraft dynamics invariant. A comprehensive set of short-term attitude and yaw response parameter variations (bandwidth and phase delay) were configured and also evaluated for select pilot station offsets. An evaluation of the various design aspects of a Translational Rate Command (TRC) control response type was conducted on the LCTR aircraft. A form of TRC using nacelle tilt to achieve longitudinal thrust vectoring was developed. The handling qualities impact of various TRC design parameters, such as the control response specifications (i.e., sensitivities and equivalent rise time) and nacelle tilt actuator characteristics (bandwidth, and position and rate-limits) were then systematically assessed in the VMS. Finally, design requirements to achieve Level 1 handling qualities in hover with this form of TRC, as well as methods to maintain good handling qualities for degraded nacelle actuator bandwidth values were also tested.

Control system configurations enforcing Attitude Command-Attitude Hold (ACAH) and Translational Rate Command (TRC) control response types were systematically appraised using methodologies derived from the Aeronautical Design Standard-33 (ADS-33) Handling Qualities Requirements for Military Rotorcraft (Ref. 16) specification. While there is no requirement to apply the military-focused ADS-33 specifications to the civilian rotorcraft, this standard provides a framework that exceeds any civilian requirements in terms of its ability to precisely quantify handling qualities and provide guidelines for good design. A rotorcraft of the scale and complexity of the LCTR2 concept will certainly need to incorporate such methodologies right from the beginning of its design lifecycle.

Results

Trade-off between disturbance rejection performance and stability margin

The comparison of various combinations of Disturbance Rejection Bandwidth (DRB) and Stability Margins for three vehicle weight classes in the ADS-33 Hover Mission Task Element (MTE) is shown in Figure 5. The Hover MTE proved to be a Level 1 task in light turbulence that degraded to Level 2 in moderate turbulence for the H-60 and the LCTR aircraft, with little variation of the average HQR shown across the stability margin cases (average HQR in the 4.2-4.3 range for the H-60, and the 4.0-4.5 range for the LCTR). The H-53 configuration was rated as Level 2 on average irrespective of the turbulence level, but more importantly, also did not vary significantly with respect to the control system cases (average HQR in the 4.3-4.8 range for all four cases in the

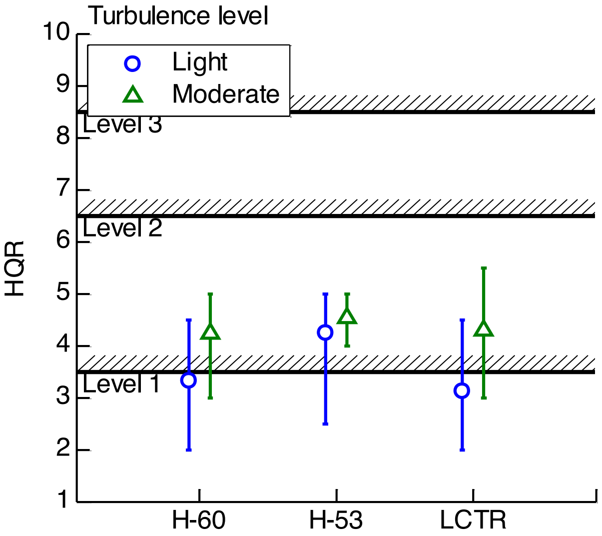


Figure 5. Composite average HQRs for varying DRB and Stability Margin combinations (Hover MTE).

moderate turbulence). Results for the ADS-33 Lateral Reposition MTE mirrored these same trends (average HQR 3.3-4.2 for all three aircraft).

In the absence of meaningful differences in the HQRs, it was instructive to distinguish the different control system configurations on the basis of the pilot comments on fundamental aircraft characteristics such as the oscillatory behavior, and predictability of the initial aircraft response. The nominal stability phase margins of ~45 deg or greater rendered the desired characteristics for the H-60, i.e., the best trade-off between disturbance rejection bandwidth and stability. Aircraft oscillatory behavior, for lower stability phase margin cases, was found to be objectionable, particularly in the roll axis. A strong argument could be made, based on the overall assessment of oscillation and predictability of the various configurations, that there was a general acceptance of reduced stability margins for increasing aircraft gross weight, with preferences for the H-53 and LCTR being for the nominal 38 and 30 deg phase margins, respectively. Consistently, the 20 deg nominal phase margin was found for all aircraft to be unacceptable, resulting in an incipient handling qualities cliff indicated on the basis of its objectionable oscillation and Pilot Induced Oscillation (PIO) propensity, as well as the unfavorable assessment of predictability.

The LCTR was regarded in general as being more stable in turbulence, or less easily disturbed by turbulence, compared to the single main rotor helicopter configurations investigated. This is attributed to the LCTR possessing higher effective damping and DRB for the same stability margins, compared to the smaller helicopter configurations investigated. A similar argument could be made about the H-53, compared to the H-60 helicopter. Therefore, the trend of pilot preference toward reducing stability margins for increasing aircraft size that is discerned is valid, to the extent that larger aircraft gross weight correlates with improved mid-term gust response characteristics.

Control response issues of large rotorcraft

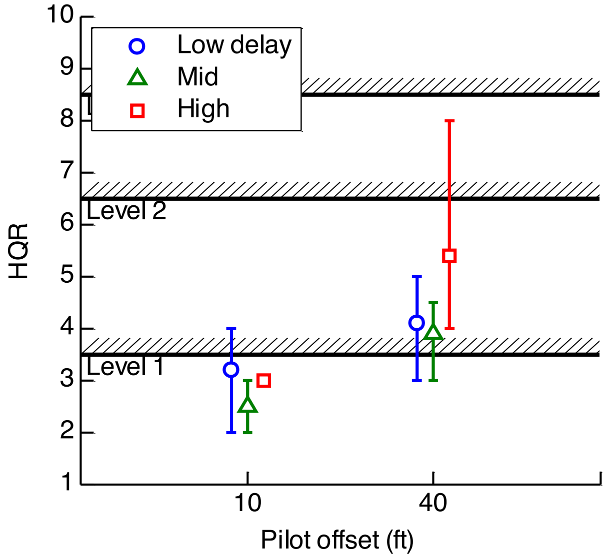
The unique characteristics of the LCTR aircraft warrant a separate discussion. The HQR comparison shown in Figure 5 suggests the relaxed Hover MTE performance requirements selected were appropriate to this class of rotorcraft, making them par with the H-60 ratings. A ±4 ft lateral-longitudinal position deviation and ±3 ft altitude deviation were appropriate for the limits of *desired* performance. *Adequate* position and altitude performance limits were set at double the desired limits, i.e., ±8 ft and ±6 ft, respectively. These performance changes effectively reflect a 25% increment in the lateral-longitudinal position requirements and a 50% increment in the altitude requirements. However, ride and handling qualities issues encountered with the LCTR, particularly in the moderate turbulence, still render it unacceptable in the context of its mission of commercial transport in all-weather operations.

Four pilots evaluated the LCTR in the DRB tests. Three of these pilots had tiltrotor flight experience. The large aircraft size, with a long moment arm between the aircraft center of gravity and the cockpit produced the most significant result differences between this aircraft configuration and the other, more conventional, single main rotor helicopters of this investigation. The impact of the long moment arm to the cockpit was immediately seen as heave motion at the cockpit due to aircraft pitch attitude changes and abrupt side-force due to yaw. The yaw-axis impact was somewhat dealt with by tuning provided by one pilot. This provided the yaw-bandwidth used for the rest of the evaluations, which was a reduced yaw control bandwidth compared to the original design. The heave motion at the cockpit due to pitch led to altered pilot control techniques. In general, pilots sought to minimize their use of pitch attitude for longitudinal position control, relying on the aircraft stabilization to do most of the longitudinal station keeping of both evaluation tasks. The precision hover task required pitch movement to initiate and terminate the inbound translation to the station keeping point. Pilots compensated by using thrust control simultaneous with the pitch control, keeping the cockpit at a constant height above ground.

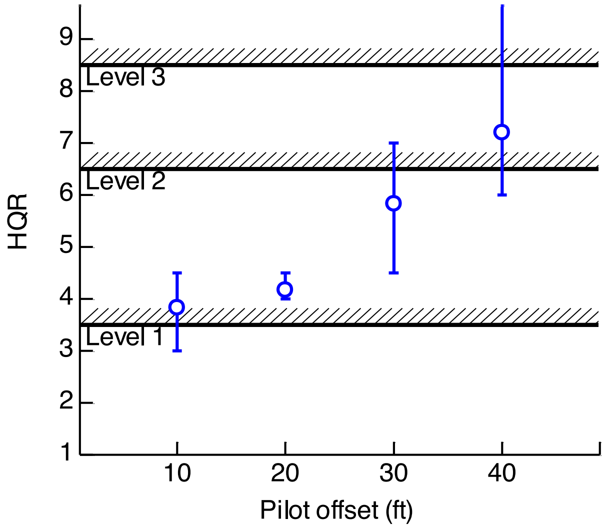
The ability of the LCTR to achieve these acceptable handling qualities, despite the ride qualities issues, is attributed to the significant control power afforded by the hingeless rotor design, which allowed satisfactory bandwidth and phase delay. While pilots disliked the ride qualities of the aircraft, they liked the fact that the particular control system allowed them, under the appropriate control technique, to achieve reasonable accuracy in task performance. The weight for the LCTR was not found to be a limitation for the achievable short-term response characteristics. In contrast, after actuator rate limiting with the H-53 was observed, the bandwidth and phase delay parameters had to be reduced (Level 2) to minimize the negative impact of actuator rate limiting. This explains the Level 2 handling qualities shown in Figure 5.

Effect of pilot longitudinal position offset

In a controlled experiment, three configurations defined *approximately* by a nominal 2.3 rad/s bandwidth, were evaluated for comparison of 10- and 40-foot pilot offsets in the Hover MTE. The key aspect of this experiment was that the dynamics of the vehicle remained invariant, and therefore the handling qualities differences were attributed only to the changes in the visual and vestibular



a). Hover MTE – varying phase delay



b). Hovering Turn MTE

Figure 6. Effect of cockpit position on HQR ratings for high response bandwidth.

cues perceived by the pilot as a function of the cockpit location. Pilot offset location was found to have a noticeable effect on the pitch (and roll, as a combined case) handling qualities, with the 40-foot case only achieving Level 2 handling qualities. Incidentally, HQR results shown in Figure 6 for the 10-foot cockpit offset are in general agreement with the ADS-33 short-term response design requirements. The Level 1 rating assigned to the high nominal phase delay case, despite the increased task altitude and moderate turbulence, is explained due to the relaxation of the Hover MTE position maintenance performance requirements.

The main deficiencies in the handling qualities for the 40-ft cases were primarily in the longitudinal axis, with the ability to compensate for longitudinal drift through control of pitch attitude deteriorating due to an objectionable heave coupling. Importantly, the evaluations confirmed a fundamental difference in the nature of the control technique required from the pilots, mainly that the heave motion at the cockpit due to pitch response led to altered pilot control techniques attempting to minimize the impact. The tiltrotor pilots noted they would ordinarily use nacelle movement for longitudinal acceleration and positioning, an option not available with the simple math model employed. Similarly, use of parallel lateral cyclic control was suggested for flat maneuver control of such a large aircraft. Significantly, pilots reported the bandwidth of response of the aircraft to be excessive and difficult to predict. Pilots also reported the degradation in the handling qualities to be accompanied by objectionable ride qualities with sudden or jerky cockpit motions in response to aggressive attitude changes.

Unlike the coupling of longitudinal and vertical control actions associated with pitch attitude changes, heading control is fully decoupled from lateral. For pilot offsets of 30 ft and greater, however, yaw maneuvering with a high bandwidth (~2.7 rad/s) control configuration conferred large, sudden, lateral accelerations, or side-forces, at the pilot station, which severely interfered with the ability of the pilot to capture a precise heading. This is reflected in Figure 6 by an increase of two (2) full handling qualities ratings in the pedal turn task, with a HQR 10 even, when increasing the pilot offset between 20 and 30 ft. Results suggest bandwidth requirements should be relaxed or pilot control input response sensitivity reduced.

Improvement of LCTR2 handling qualities with TRC

Select ACAH and TRC configurations were chosen for comparison in the Lateral Reposition and Hover MTEs. When selecting the LCTR2 short-term attitude response characteristics for comparison, care was taken to ensure sensible ride qualities, thus precluding higher bandwidth control response configurations. A methodical verification of various configurations was conducted with the project pilot prior to the commencement of the experiment. The outcome of this process was that it confirmed the trends from previous experiences in that higher response bandwidths would result in negative ride qualities. The comparison ACAH therefore represents the best trade-off between handling and ride qualities.

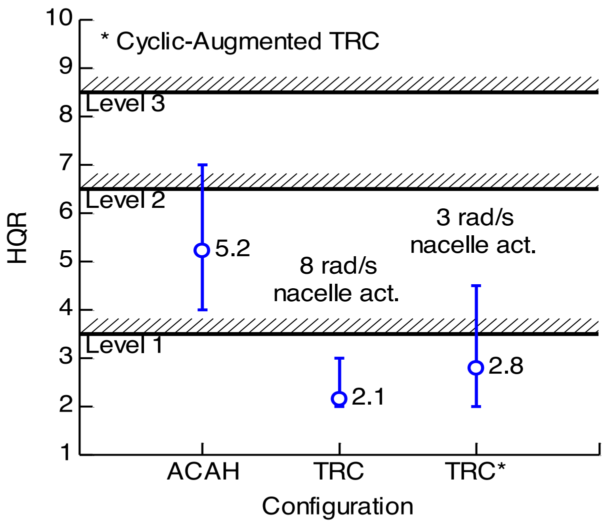


Figure 7. Comparison of LCTR2 handling qualities for select TRC implementations relative to ACAH in the Hover MTE.

Ratings comparing select ACAH and TRC configurations in the Hover MTE are shown in Figure 7. This figure shows a drastic improvements in the average ratings for the two TRC configurations (5.2 for ACAH, 2.1 for a TRC variant with 8 rad/s bandwidth nacelle actuators, and 2.8 for the so-called "cyclic-augmented" TRC). The TRC results presented in Figure 7 are for a 10 ft/s/in sensitivity and a 5 s first-order response equivalent rise time. These results illustrate the substantial potential handling qualities improvements which are attainable with a TRC response type, provided necessary nacelle actuator bandwidth is installed, and how good handling qualities can be retained by quickening of the TRC response via rotor cyclic inputs with a reduced nacelle bandwidth. Minimization of pitch attitude changes curtailed the compelling pitch/heave perception issues associated with the center of gravity offset. Pilots described the lack of bank as "odd", but agreed it was possibly the right way to fly this type of aircraft, and the HQRs confirmed their preference and better performance.

Considering the various challenges and issues connected with the ACAH approach, the use of the nacelles in the TRC scheme was found to be an attractive solution from a handling qualities and flight control perspective. The results presented in Figure 7 have shown that a control law can be devised to confer Level 1 handling qualities using such a scheme. For this improvement to be attainable, nacelle actuators needed to provide enough bandwidth of response (>4 rad/s) to ensure satisfactory performance of the closed-loop control system. The quickening of the TRC response afforded by the use of longitudinal cyclic control was quantified at 200 ms of phase delay, and critically, this reduction put it at ~450 ms, and thusly, below the 500 ms identified for Level 1 handling qualities. One other aspect of the TRC implementation using nacelles for the longitudinal velocity control is the consequence of nonlinear phenomena such as rate limits of which saturation was one of the principal causes of a handling qualities cliff encountered. At small pilot input Root Mean Square (RMS) values, the systems are effectively linear and there is no perceivable difference in the phase delay, but for larger RMS inputs, the rate limiting effect becomes prevalent, increasing the effective amount of delay. A high phase delay value alone is poor, but a strong dependency of worsening phase delay on the pilot input amplitude leads to a highly nonlinear and negative control characteristic. If the input amplitude can be kept small then the poor handling qualities are "avoided" – this is the core reason for the handling qualities cliff, in that if the input is too large a large of amount delay is experienced and thus likely to increase the pilot gain to compensate, induce further large inputs, and thus further exacerbate the problem.

Playing a potentially beneficial role, the system overall phase delay for the cyclic-augmented control case is not only lower than in un-augmented cases, but notably, the rise in phase delay with amplitude is also eliminated. Effectively the vehicle dynamics would "appear" much more "linear" with no changes in response characteristics with changing pilot input amplitude – a significantly improved handling qualities characteristic.

One final critical aspect of the TRC implementation using nacelles was the necessity to reduce the impact of a non-minimum phase pitch response associated with the rotor flap-back dynamics, in particular with high bandwidth nacelle actuators. This response dynamic manifested itself to the pilots as a noticeable response in pitch that was opposite to the cyclic inceptor input (e.g., nose up for a forward control input), was found to be very troubling to the pilots, and was corrected by cross-feeding the nacelle conversion rate signal to the longitudinal cyclic control.

Conclusions

The following key conclusions were drawn from this series of experiments:

- Rotorcraft configurations of increasing size (gross weight) exhibited a preferable trade-off between disturbance rejection bandwidth and stability margin allowing for relaxed attitude feedback phase margins in hover and low speed.
- An ACAH response type for the precise hover control of an aircraft with a large (i.e., greater than 30 ft) pilot offset from the center of gravity achieved Level 2 handling qualities, at best,

when operating in “moderate turbulence” environmental conditions. At such large pilot offsets from the center of gravity, aircraft dynamics exhibiting a high bandwidth attitude response (in all axis) were subjected to objectionable impulsive load factors at the pilot station (a ride qualities issue) and unpredictable aircraft response (a handling qualities issue).

- TRC response types with minimal attitude response were unanimously preferred over the attitude-based ACAH, and TRC enabled Level 1 handling qualities in hover, even in turbulent conditions. The various actuator dynamics, and control crossfeeds and feedback aspects of the TRC control system design have an impact on the longitudinal short-term position response phase delay. If the phase delay becomes excessive, objectionable oscillatory characteristics in the longitudinal translational axis degrade the handling qualities, and can lead to Pilot Induced Oscillations.

Effect of Control System Augmentation on Handling Qualities in DVE

In June 2013, NASA and the U.S. Army jointly conducted a simulation experiment in the VMS that examined and quantified the effects of partial-authority control system augmentation on handling qualities and task performance in both good and degraded visual environments (Ref. 17).

Introduction

The hazards associated with helicopter flight in Degraded Visual Environments (DVE) have led to a number of accidents, both in military operations, particularly in brownout conditions (Ref. 18), and in civilian operations with inadvertent flight into Instrument Meteorological Conditions (IMC) and loss of situational awareness resulting from degraded visual conditions (Ref. 19) being significant contributors. For small helicopters, a major contributor to the high accident rate is their inherent instability without advanced control modes. This instability can lead to excessive pilot workload when flying in IMC and DVE. ADS-33 defines control system response type requirements for DVE as a function of Usable Cue Environment (UCE), or the “quality” of the visual conditions. In degraded visual conditions (UCE>1), ADS-33 requires a minimum Attitude Command/Attitude Hold (ACAH) response type, along with Rate Command/Direction Hold (RCDH) and Rate Command/Height Hold (RCHH) depending on the specific Mission Task Element (MTE), in order to obtain Level 1 handling qualities.

The mitigation of DVE has received increased attention recently with many research efforts typically focusing on one or more of the following areas: 1. improved sensors to detect the terrain and obstacles around the rotorcraft, including at night and in low light conditions, and through fog, rain, dust, sand, etc.; 2. improved heads-up and heads-down displays to provide the pilot with improved situational awareness; and, 3. improved flight controls through advanced control modes to reduce pilot workload and improve flight precision. The combination of these three key technologies for safe and effective operations in DVE comprise what has been commonly referred to as the “three legged DVE stool” (Ref. 20).

Focusing on the flight control “leg” of research, a number studies of accident records such as Ref. 21 & 22 have shown large proportion of accidents (excluding mechanical failures) occurred for small single main rotor helicopters in GVE that were not augmented or had only “limited” rate stabilization, or were attributed to “loss of control” in degraded visual conditions such as “inadvertent IMC” (IIMC). Ref. 21 proposes that even small improvements to helicopters stability and control could dramatically reduce accident rates. This parallels Ref. 22, which states that the primary cause of accidents was poor pilot situational awareness and spatial disorientation in which poor or inappropriate mechanical flight control characteristics resulting in degraded handling qualities. Ref. 22 suggested that serious consideration must be given to improvements in regulations and requirements, for operating procedures, pilot training and vehicle characteristics to eliminate configurations with poor handling qualities, particularly in DVE and high workload situations.

For military operations, Ref. 18 states that DVE caused by brownout and whiteout account for almost half of the Air Force rotorcraft airframe losses, and are the leading cause of airframe losses for the Army. One of the major causes of military rotorcraft hover & low-speed mishaps in DVE is undetected drift resulting in dynamic aircraft rollover leading to main- and tail-rotor strikes. An earlier study by Key (Ref. 23) examined rotorcraft accidents due to pilot error over a period from 1986 to 1998. An outcome of this study showed that control laws optimized for daytime operations typically result in poor handling qualities in DVE and at night. Ref. 23 concluded that handling qualities improvements are possible with flight control augmentation that provides ACAH possible even with the limited authority systems that currently exist in the helicopter fleet.

References 22 & 24 also featured experiments examining the effects of handling qualities and displays in hover and low-speed flight in reduced visibility conditions. The results indicated that rate and attitude command may be used for varying levels of partial IMC, but that TRC is required for hover/low speed operations in zero visibility and concluded that the addition of displays were not a substitute for control system augmentation.

A recent flight test (Ref. 25) studied the effect of optimizing and augmenting the OH-58D Rate Command stability and control augmentation system in in DVE. Comparisons of handling qualities ratings were made between the baseline OH-58D Rate Command and an optimized short-term ACAH control systems in select ADS-33 MTEs in both GVE and DVE. The optimized short-term ACAH (st-ACAH) control system provided better handling qualities in both GVE and DVE, but that pilots observe a significant difference between the baseline and st-ACAH designs in more dynamic maneuvers, such as the Sidestep, Acceleration/Deceleration MTEs and the run-in to the Hover MTE, confirming that the benefits with st-ACAH come in high-bandwidth tasks, such as the deceleration and station keeping portions of the Hover MTE.

Objectives

The objectives of this study were to investigate and quantify the effect of control system augmentation on handling qualities and pilot task performance in GVE and DVE, including:

- Assessment of the benefits of increased control augmentation with a partial authority flight control architecture for missions in GVE and DVE.
- Initial development of mission task elements and evaluation metrics appropriate for civilian missions in DVE, including Medevac and EMS operations.
- Refinement of control system and handling qualities requirements for civilian Medevac/EMS and military scout helicopters.

Experimental Setup

The vehicle model used for this experiment was representative of the OH-58D which has similar size, weight (~5,500 lbs) and performance, and the same 4-bladed rotor system as the Bell 407 helicopter that is commonly used for Medical Evacuation (Medevac) and Emergency Medical Services (EMS) roles. The OH-58D includes a standard three-axis (pitch, roll, and yaw) partial authority (±10%) Stability and Control Augmentation System (SCAS), while the Bell 407 can be fitted with an aftermarket SCAS, such as the Cobham HeliSAS analog autopilot and stability augmentation system (Ref. 26).

State-space models of the flight dynamics of the aircraft were extracted using system identification from flight-test data from previous research (Ref. 25) at flight speeds of hover and 80 knots. These point models were ‘stitched’ together along with trim data to develop a continuous dynamics model (Ref. 27) that is valid up to about 100 knots. The Control Equivalent Turbulence Input (CETI) model (Ref. 28) was configured for the OH-58D to provide turbulence for the simulation.

Four different control system concepts were evaluated in this experiment: Firstly, a **Rate Command (RC)** system, the baseline control system of the OH-58D. This control system includes rate stabilization via an angular rate feedback and an input feed-forward loop for control augmentation. The RC control system is representative of the actual OH-58D as well as many of the helicopters that are used for civil EMS type missions today, and so it was selected for this study. The second was a **Short-term Attitude Command/Attitude Hold (st-ACAH)** control system. This was developed as a possible upgrade to the OH-58D SCAS (Ref. 12) and uses lagged-rate gains, equivalent to washed-out attitude feedback to achieve a st-ACAH response type in pitch and roll. The st-ACAH response type is provided in hover up to 40 knots, and is blended to RC from 40 to 60kts. This control system was designed to meet ADS-33 Level 1 requirements but with improved damping over the rate command system. The third and fourth control systems were **Modernized Control Laws (MCLAWS), and MCLAWS with Position Hold (MCLAWS+PH)**. MCLAWS was developed to build on the good short-term response characteristics of the st-ACAH control laws, but extend the attitude hold capabilities to steady-state using a direct attitude measurement that is available on most modern helicopters. MCLAWS achieves an ACAH response type in pitch and roll using existing partial-authority SCAS actuators with special attention paid to minimizing the saturation of the SCAS servos. In the yaw axis, MCLAWS includes a Rate Command/Direction Hold (RCDH) mode, which captures and maintains a heading once the pilot releases the pedals. As with the st-ACAH control systems, MCLAWS are blended to rate command from 40 to 60 knots. It should be noted that sensors providing attitude measurements would need to be added to the aircraft to achieve an MCLAWS control system.

Facility

The experiment was conducted in the VMS with the center and collective sticks and pedal control inceptors were selected to closely match those of the OH-58D and installed for the right-hand evaluation pilot cockpit seat. For the Position Hold mode, a deceleration to hover is initiated below 5 knots and with the stick in detent. When the speed drops below 0.5 knots, position hold is engaged. The pilot can ‘adjust’ the hover position with the ‘hat’ switch on the cyclic control inceptor. A single “click” of the ‘hat’ is 1-foot translation, while holding a deflection is a translational rate of 4 ft/sec.

Figure 8. Night Vision Goggles (NVGs) mounted to pilots' helmet.

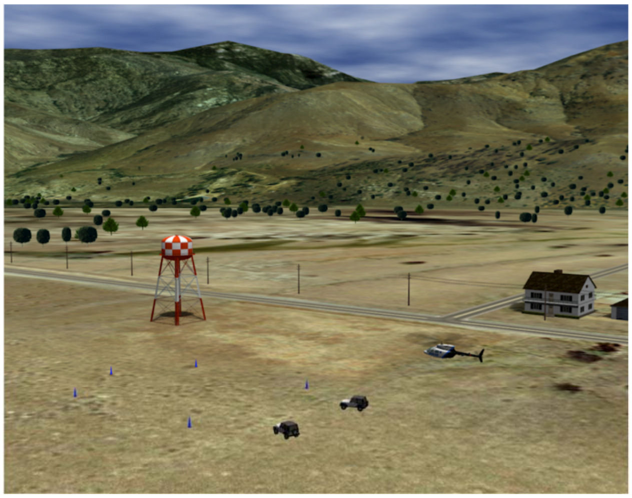


Figure 9. Vicinity of landing zone for EMS Approach task, helicopter descending to cone marked area.

Carefully tailored visual scenes of the ADS-33 and EMS evaluation tasks were developed with attention to task cueing and visual textures in both GVE and DVE conditions. For this experiment, DVE was simulated primarily with the pilots wearing real Night-Vision Goggles (NVGs) in a simulated night visual scene, as well as a scene to be flown unaided by goggles. Figure 8 shows a photo of the NVGs mounted to the pilots' helmet. The goggles used were ITT Exelis Aviator's Night Vision Imaging System (ANVIS) AN/AVS-6.

Evaluation Tasks and Procedures

The simulation evaluation maneuvers comprised of the ADS-33 Hover, Sidestep, Acceleration/Deceleration, and Pirouette Mission Task Elements (MTEs), (only result for the Hover MTE are included in this paper), as well as a new Emergency Medical Services task that consists of an approach and landing at a minimally prepared remote landing site. Degraded visual environments were simulated. The Usable Cue Environment (UCE) was measured for this simulation experiment, and found to be UCE=1 in good visual environments and UCE=2 in DVE with night vision goggles.

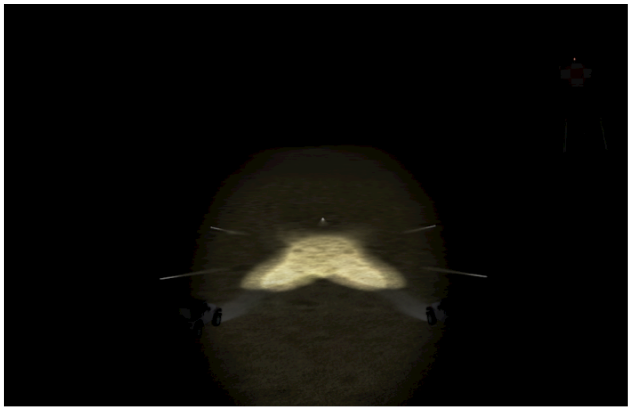


Figure 10. Screenshot showing pilot unaided night view of the landing zone during final approach.

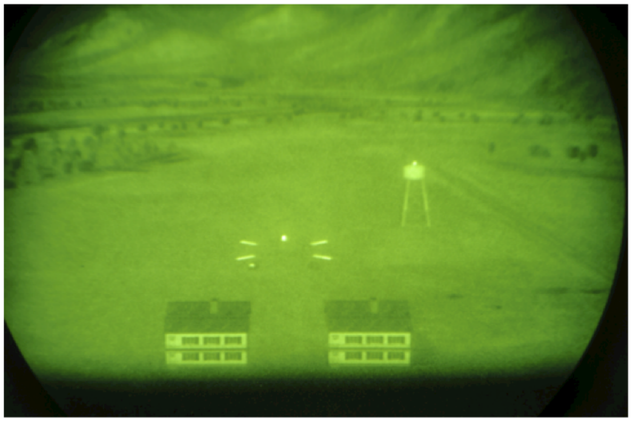


Figure 11. View of landing zone during final approach taken through NVGs.

The new civilian EMS-type mission/task (EMS Approach MTE) consisted of a maneuver starting at 65-knots level flight at 250-feet AGL on a heading 90-degree offset to the final approach path. Figure 9 shows a picture of the general EMS Approach MTE landing zone, centered among the simulated buildings and water tower. The pilot would then make a right descending, decelerating turn to an altitude of 200ft and a speed of 15 knots to begin the descent on a 12-degree glideslope to land in the center of a 100x100ft landing zone marked by cones.

Figure 10 shows the pilot perspective of the unaided night scene near the landing zone during final approach. In the night scene, the cones used in GVE marking the landing zone were replaced by simulated flashlights pointing towards the center of the landing zone. The headlights of two vehicles were used to illuminate the center of the landing zone, and an ownship mounted spotlight is also illuminating the landing zone. Figure 11 shows a view of the landing zone through the NVGs. The NVG scene did not use the vehicle headlights and ownship spotlight.

A moderate level of turbulence was used throughout the simulation experiment. This turbulence level was set as a trade-off to provide adequate disturbances to increase pilot workload for task performed in GVE, while not providing unnecessarily high workload in more difficult tasks, such as the Hover MTE in DVE with the Rate Command control system. All of the maneuvers were flown with no steady winds. The EMS Approach MTE was flown in DVE unaided as well as DVE with NVGs since the illuminated landing zone provided sufficient cueing for the approach and landing to be flown in DVE unaided. The ADS-33 MTEs that included simulated hover and cueing boards, and lines and cones on the ground, did not provide enough cueing to the pilot when flown in DVE unaided; therefore, they were in DVE with NVGs only.

Results

Over 1400 data runs were performed as part of this experiment with 12 different evaluation pilots, including nine experimental test pilots (XPs) from NASA, U.S. Army, U.S. Navy and FAA, and 3 non-XPs that had extensive OH-58, DVE and/or EMS experience.

Results showed that HQRs were improved with a control system providing short-term attitude response over a rate command system, although the improvements were not sufficient to produce Level 1 handling qualities in degraded visual environments. Results for an Attitude Command/Attitude Hold control system showed that borderline Level 1 handling qualities could be achieved in degraded visual environments, and the 10% authority stability augmentation system was adequate to obtain these handling qualities ratings.

Hover MTE

The effect of control augmentation on Cooper-Harper handling qualities ratings for the ADS-33 Hover MTE in GVE and DVE with NVGs is shown in Figure 12. This figure also shows the flight test data for the OH-58D for GVE and DVE flight with the baseline rate response control system.

In GVE, all of the pilots provided handling qualities ratings for the RC control system, indicating that this is a solidly Level 2 aircraft for this task in GVE. This is comparable with the OH-58D flight test results with the same RC control architecture, where the two pilots both provided handling qualities ratings of 4. ADS-33 indicates that a RC system is the minimum response type required for Level 1 Handling Qualities in GVE (UCE=1), however for this particular aircraft in the Hover MTE, the RC system produced Level 2 handling qualities. For the st-ACAH control system the average handling qualities rating is borderline Level 1, an improvement of about 1.0 HQR when compared with the RC control system. This indicates that with a moderate augmentation to the RC control system, Level 1 handling qualities can be achieved in GVE for the Hover MTE. These results are comparable with the flight test results for the OH-58, where both pilots gave a HQR3 for st-ACAH in GVE.

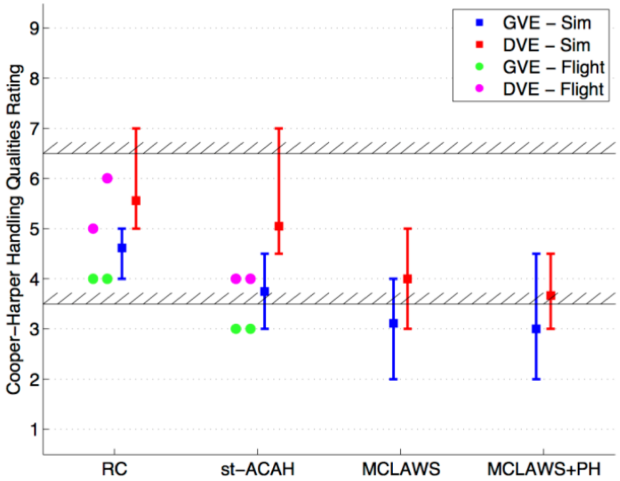


Figure 12. Hover MTE handling qualities ratings from VMS simulation and flight test (Ref. 25).

Further augmentation with the MCLAWS and MCLAWS+PH response types produced a Level 1 aircraft with average HQR ratings of about 3.0 for both ACAH control systems. These results also show that the addition of Position Hold does not significantly improve the handling qualities ratings for the Hover task in GVE.

For DVE, handling qualities ratings obtained with the RC control system were comparable with those from flight test data. For st-ACAH, the improvement is only about 0.5 HQR. This is slightly degraded from the flight test results where both pilots provided a HQR of 4 for the Hover MTE in DVE. In comparing all of the Hover MTE simulation results with the flight test data, it is seen that the flight test handling qualities ratings are consistently better than those from the simulation.

A more substantial improvement in handling qualities ratings in DVE was seen with the MCLAWS response type where the improvement is more than 1 rating point. The addition of Position Hold in DVE improves the ratings by an average of 0.5 to be borderline Level 1, These simulation results are not directly comparable to the ADS-33 requirements for Level 1 handling qualities in DVE (UCE=2) since the MCLAWS control system did not include Rate Command Height Hold (RCHH), the

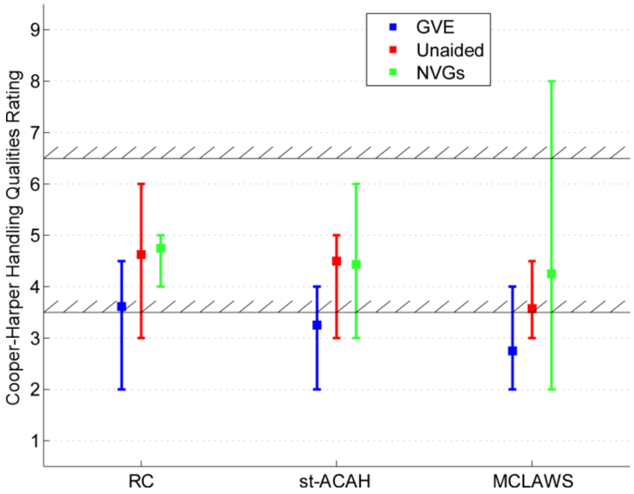


Figure 13. EMS Approach MTE handling qualities ratings versus response type in GVE and DVE.

addition of which would likely have reduced the vertical axis workload and conferred solid Level 1 handling qualities.

EMS Approach MTE

Figure 13 shows handling qualities ratings in the EMS Approach MTE for GVE and DVE with the RC, st-ACAH and MCLAWS control systems. For GVE, the aircraft is borderline Level 1 with an average handling qualities rating of about 3.5 for the RC control system and improves to Level 1 with the st-ACAH and MCLAWS control systems. A similar trend is obtained with DVE unaided and DVE with NVGs for all of the control systems shown. The HQRs are Level 2 with an average rating of 4.5 for the RC and st-ACAH control system, and improving to borderline Level 1 with MCLAWS with an average rating of 3.5. With the descending approach in this MTE, the potential benefits of adding altitude hold (RCHH) to the MCLAWS control system may be less for the EMS Approach MTE than for the Hover MTE. Pilots commented that in DVE they could not pick up speed and vertical velocity changes as quickly or as accurately as in GVE, particularly during the initiation and tracking of the glideslope, which was a key factor in the degraded handling qualities ratings in DVE.

It is worth noting that saturation of the actuators of the 10% authority SCAS was not a factor in the handling qualities shown in Figure 13 for the EMS Approach MTE. This indicates that a 10% authority SCAS would generally be sufficient to provide good handling qualities from st-ACAH response type with software upgrades, or an ACAH response type with attitude feedback for this particular MTE.

The improvement in HQRs from RC to st-ACAH for the EMS Approach (Figure 13) is smaller than the improvement seen for the Hover MTE (Figure 12). This is due to the fact that the st-ACAH control system primarily improving the short-term response characteristics, which are less important for the EMS Approach MTE than for the Hover MTE. The Hover MTE also requires the pilot to be more aggressive to attain the level of precision required by the task, and is a higher bandwidth task than the EMS Approach MTE.

The EMS Approach MTE was also viewed favorably by all of the pilots as representative of EMS type operations. One pilot commented: “Representative of civilian operations and was able to highlight the differences in handling qualities and workload between the different control systems.”

Conclusions

The following key conclusions were drawn from this experiment:

- The handling qualities ratings for the Hover MTE in this simulation experiment are consistent with those from the OH-58D flight test for the RC and st-ACAH control systems, providing important anchor points for the results of the simulation experiment.

- Additional augmentation with st-ACAH and MCLAWS provided improved handling qualities and lower pilot workload, allowing the pilot to back out of the control loop and lower their control bandwidth. This is particularly true of the tasks that required high pilot control bandwidth, such as the ADS-33 Hover MTE.

- The 10% authority stability augmentation system was sufficient to achieve an ACAH response type with the MCLAWS control system up to the transition speed of 40 knots, and actuator saturation was not a factor in the handling qualities ratings for any of the MTEs examined during this simulation experiment.

Concluding Remarks

This paper presented an overview of recent rotorcraft flight dynamics and control research at NASA. The paper described the Cooper-Harper Handling Qualities Rating scale that has for many years been a key differentiator in evaluating handling qualities for current and future rotary wing vehicles and advance flight control response types. The Vertical Motion Simulator was also presented since it continues to be a key facility for rotary wing flight control and handling qualities research due to its high-fidelity simulation environment and large motion platform, and was used to generate the handling qualities results shown in this paper. Finally this paper described two recent flight dynamics and control research efforts performed at NASA. The first was an examination of flight control and handling qualities aspects of large rotorcraft, and the second was an examination of the effect of control system augmentation on handling qualities for current civil rotorcraft, like those currently used for Emergency Medical Service type operations.

References

1. Cooper, G.E. and Harper, R.P., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, April 1969.

2. Aponso, B. L., Tran, D. T., and Schroeder, J. A., "Rotorcraft Research at the NASA Vertical Motion Simulator," presented at the American Helicopter Society 64th Annual Forum, Montreal, Canada, April 29 - May 1, 2008.

3. Blanken, C.L., Lusardi, J.A., Ivler, C.M., Tischler, M.B., Decker, W.A., Malpica, C.A., Berger, T., and Tucker, G.E., Höfinger, M.T., "An Investigation of Rotorcraft Stability – Phase Margin Requirements in Hover," Proceedings of the American Helicopter Society 65th Annual Forum, Grapevine, TX, May 27-29, 2009.

4. Malpica, C. A., Decker, W. A., Theodore, C. R., Blanken, C. L., and Berger, T., "An Investigation of Large Tilt-Rotor Short-term Attitude Response handling Qualities Requirements in Hover." Proceedings of the American Helicopter Society 66th Annual Forum, Phoenix, AZ, May 11-13, 2010.

5. Lawrence, B., Malpica, C. A., and Theodore, C. R., "The Development of a Large Civil Tilt-rotor Simulation for Hover and Low-Speed Handling Qualities Investigations," presented at the 36th European Rotorcraft Forum, Paris, France, September 7-9, 2010.

6. Malpica, C. A., Decker, W. A., Theodore, C. R, Lawrence B., Lindsey, J., and Blanken, C. L., "An Investigation of Large Tilt-Rotor Hover and Low Speed Handling Qualities Requirements." Proceedings of the American Helicopter Society 67th Annual Forum, Virginia Beach, VA, May 3-5, 2011.

7. Lawrence, B., Malpica, C. A., Theodore, C. R., Decker, W. A., and Lindsey, J., "Flight Dynamics Aspects of a Large Civil Tilt-rotor Simulation using Translational Rate Command," Proceedings of the American Helicopter Society 67th Annual Forum, Virginia Beach, VA, May 3 - 5, 2011.

8. Malpica, C. A., Theodore, C. R., Lawrence, B., Lindsey, J. E., and Blanken, C. L., "Handling Qualities of a Large Civil Tiltrotor in Hover using Translational Rate Command," Proceedings of the American Helicopter Society 68th Annual Forum, Fort Worth, TX, May 1-3, 2012.

9. Acree, Jr., C. W., Yeo, H., and Sinsay, J., Performance Optimization of the NASA Large Civil Tiltrotor, NASA/TM-2008-215359, June 2008.

10. Johnson, W., Yamauchi, G. K., and Watts, M. E., "NASA Heavy Lift Rotorcraft Systems Investigation," NASA/TP–2005-213467, December 2005.

11. Blake, M., Smith, J., Wright, K., Mediavilla, R., *et. al.*, "Advanced Vehicle Concepts and Implications for NextGen," NASA/CR-2010-216397, 2010.

12. Wilkerson, J. B., and Smith, R. L., "Aircraft System Analysis of Technology Benefits to Civil Transport Rotorcraft," NASA/CR–2009-214594, 2009.

13. Young, L. A., Chung, W. W., Paris, A., Salvano, D., Young, R., Gao, H., Wright, K., and Cheng, V., "Civil Tiltrotor Aircraft Operations," 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Virginia Beach, VA, September 2011.

14. Chung, W. W., Linse, D., Paris, A., Salvano, D., Trept, T., Wood, T., Gao, H., Miller, D., Wright, K., Young, R., and Cheng, V., "Modeling High-Speed Civil Tiltrotor Transports in the Next Generation Airspace," NASA/CR–2011-215960, 2011.

15. Chung, W. W., Salvano, D., Rinehart, D., Young, R., Cheng, V., and Lindsey, J., "An Assessment of Civil Tiltrotor Concept of Operations in the Next Generation Air Transportation System," NASA/CR–2012-215999, 2012.

16. Anon., "Handling Qualities Requirements for Military Rotorcraft", Aeronautical Design Standard-33 (ADS-33E-PRF), US Army Aviation and Missile Command, March 21, 2000.

17. Theodore, C. R., Malpica, C. A., Lawrence, B., Blanken, C. L., Tischler, M. B., Lindsey, J. E., Berger, T., "Effect of Control System Augmentation on Handling Qualities and Task Performance in Good and Degraded Visual Environments," Proceedings of the American Helicopter Society 70th Annual Forum, Montreal, Canada, May 20-22, 2014.

18. Anon., “Aviation Safety Technologies Report,” Acquisition and Technology Programs Task Force (ATP TF), Department of Defense Aviation Safety Technologies Report, Washington, DC: Defense Safety Oversight Council, Office of the Under Secretary of Defense for Personnel and Readiness, Program Budget Request 10-15, Program Decision Memorandum, April 30, 2009.

19. Anon., US Joint Helicopter Safety Analysis Team: Year 2000 Report to the International Helicopter Safety Team, September 2007.

20. Brown, K., “Surviving DVE: Q&A with Tony Pots, ”Rotor & Wing, Vol. 46, No. 9, September 2012, pp. 34-37.

21. Dugan, D., Delamer, K.J., “The Implications of Handling Qualities in Civil Helicopter Accidents Involving Hover and Low Speed Flight”, NASA/TM—2005-213473, November, 2005.

22. Anon., ”Helicopter Flight in Degraded Visual Conditions”, CAA Paper 2007/03, Safety Regulation Group, CAA, September 2007.

23. Key, D.L., “Analysis of Army Helicopter Pilot Error Mishap Data and the Implications for Handling Qualities”, 25th European Rotorcraft Forum, Rome, Italy, September 14-16th, 1999.

24. Hoh, R. H., Baillie, S. W., Morgan, J. M., “Flight Investigation of the Tradeoff between Augmentation and Displays for NOE Flight in Low Visibility,” Presented at the Midwest Regional National Specialist’s Meeting on Rotorcraft Flight Controls and Avionics, American Helicopter Society, Cherry Hill, New Jersey, October 13-15, 1987.

25. Berger, T., Tischler, M.B., Blanken, C.B., Fujizawa, B.T., Harding, J.W., Borden, C.C., Cothren, L.E., Wright, J.J., Arterburn, D.R., and Pfrommer, M.R., “Improved Handling Qualities for the OH-58D Kiowa Warrior in the Degraded Visual Environment,” presented at the American Helicopter Society 67th Annual Forum, Virginia Beach, Virginia, May 3-5, 2011.

26. Stephens, Ernie, “Cobham Displays HeliSAS on Bell 407,” Rotor & Wing, http://www.aviationtoday.com/rw/topstories/Cobham-Displays-HeliSAS-on-Bell-407_78885.html, April 1, 2013.

27. Tischler, M. B. and Remple, R. K., *Aircraft and Rotorcraft System Identification: Engineering Methods and Flight Test Examples Second Edition*, AIAA, 2012.

28. Lusardi, J. A., von Gruenhagen, W., Seher-Weiss, S., "Parametric Turbulence Modeling for Rotorcraft Applications, Approach, Flight Tests and Verification," presented at the Rotorcraft Handling Qualities Conference, University of Liverpool, UK, Nov 2008.