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Rotorcraft Research at the NASA Vertical Motion Simulator

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In the 1970's the role of the military helicopter evolved to encompass more demanding missions including low-level nap-of-the-earth flight and flight in severely degraded visual environments. The Vertical Motion Simulator (VMS) at the NASA Ames Research Center was built to provide a high-fidelity simulation capability to research new rotorcraft concepts and technologies that could satisfy these mission requirements. The VMS combines a high-fidelity large amplitude motion system with an adaptable simulation environment including interchangeable and configurable cockpits. In almost 30 years of operation, rotorcraft research on the VMS has contributed significantly to the understanding of rotorcraft performance, handling qualities, flight control, and guidance and displays. These contributions have directly benefited current rotorcraft programs and flight safety. The realistic motion cueing capability in the VMS was also used to research pilot cueing and simulation fidelity, providing a fundamental understanding of pilot cueing modalities and their effect on simulation fidelity.

I. Introduction

IN the 1960's, the role of the military helicopter evolved from primarily a utility role to encompass more demanding roles including ground assault transport and ground attack. Recent combat experience in the 1970's indicated that low-level nap-of-the-earth (NOE) flight, air-to-air combat, and night operations were necessary future tactical capabilities for rotorcraft. Designing a new generation of rotorcraft to meet these evolving and increasingly demanding missions required a significant expansion and improvement of the understanding of rotorcraft performance and flying characteristics. Acquiring this understanding and applying it to develop new technologies and rotorcraft designs that could accomplish these more demanding missions with improved safety required fundamental research. The single-main-rotor helicopter was the most common rotorcraft configuration at the time. With unstable dynamics at low-speed and significant cross-coupling between axes of control, the single-rotor helicopter is demanding to fly and requires closed-loop pilot control at all times. Expanding the understanding of rotorcraft flying characteristics, therefore, required a high-fidelity flight simulation environment. This requirement was met at NASA Ames Research Center using a combination of ground-based simulation, and in-flight simulation using variable stability research rotorcraft.

For almost four decades, the Vertical Motion Simulator (VMS) and its predecessor, the Flight Simulator for Advanced Aircraft (FSAA) at NASA Ames Research Center, have served as cornerstones for rotorcraft research. Built in 1969, the FSAA was originally designed for fixed-wing aircraft research and, as it was increasingly used for rotorcraft research, the need for improved motion fidelity, particularly in the vertical axis, became evident (Ref. 1). The VMS was designed to meet this need and became operational in 1979. The VMS included the highest fidelity motion system in the world, a distinction it holds to this day. In addition to high-fidelity vertical and lateral motion cueing, the VMS included an interchangeable cab system with high-fidelity visual displays of the outside world and adaptable cockpit interfaces with accurate control feel systems, flight instruments and displays.

The need to expand the understanding of rotorcraft performance and flying qualities was recognized by the Army who, in collaboration with NASA, began a program to meet this need. Together with research on rotorcraft, a parallel and interacting stream of studies examined human pilot cueing and the level of simulation fidelity required to accurately recreate the pilot-rotorcraft interaction in flight. In almost three decades of operation, simulation studies on the VMS by a team of NASA and U.S. Army Aeroflightdynamics Directorate (AFDD) researchers at the Ames Research Center generated a majority of this data. Jet powered V/STOL aircraft and technologies were also

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evaluated on the VMS through collaboration between NASA and industry. This paper focuses on rotorcraft and provides an overview of rotorcraft research at the VMS - summarizing the impact of this work on current and future rotorcraft design, development, procurement, and operations. The research is grouped into six streams: handling qualities; guidance and displays; simulation fidelity and cueing; flight control design and evaluation, specific programs; and tilt-rotor. Following a description of the present capabilities of the VMS and the genesis of its design, this paper summarizes the research conducted in each of these streams.

II. Description of the VMS

The VMS combines a high-fidelity simulation capability with an adaptable simulation environment that enables customization for numerous human-in-the-loop research applications. The distinctive feature of the VMS is its unparalleled large amplitude, high-fidelity motion capability. An overall high level of simulation fidelity is achieved by combining this motion fidelity with realistic visual and cockpit interfaces. Interchangeable cabs allow different crew vehicle interfaces and vehicle types to be evaluated with rapid turnaround times between simulation projects.

The Interchangeable Cab (ICAB) capability allows the cockpit to be tailored to the research application. The VMS has five portable ICABs with different out-the-window visual fields-of-view. For each simulation, an ICAB is selected and equipped to meet the study's requirements and then tested with the complete simulation environment without motion. Configuring the cab includes installation of flight controls, flight instruments and displays, and seats (Fig. 1). Following cab configuration and checkout, the ICAB is transported and installed on the motion system. The ICAB capability, simulation architecture, and resources enable the VMS facility to conduct fixed-base and moving-base simulation studies simultaneously.

Fixed-base Cab Interior Moving-base

Figure 1. VMS Transport Cab on and off the motion system

The high-fidelity flight controls are heavily modified and optimized McFadden hydraulic force-loader systems (Ref. 2). A custom digital-control interface allows for comprehensive adjustment of the controller's static and dynamic characteristics. Force-loader characteristics may be varied during simulated flight as necessary for studying pilot cueing concepts using inceptors. A variety of aircraft manipulators, ranging from the regular column-and-wheel type to conventional rotorcraft controls and side sticks, are available and may be combined with the force-loader systems.

A Rockwell-Collins EPX-5000 image generation system creates the out-the-window visual scene and provides a high-resolution and complex visual environment at update rates exceeding 60Hz. Fifteen channels are available, allowing up to three different simulation experiments to be conducted simultaneously in the facility. In-house graphics expertise is used to customize the visual databases to meet widely varying simulation requirements. Separate graphics processors generate the content for the primary flight displays, head-up displays, sensor imagery, etc, which can be fully customized.

All the essential elements of the simulation are linked with the host environment through a dedicated network and the simulation is managed from a fully equipped control room. The flexible simulation architecture makes it convenient to interface and evaluate custom software and hardware modules. This capability may be used to evaluate sensors, vehicle dynamic models, flight control systems, etc.

A. Motion System Description

The VMS motion system, shown in Fig. 2, is an uncoupled, six-degree-of-freedom, combined electro-mechanical/electro-hydraulic servo system (Ref. 3). It is located in, and partially supported by, a specially constructed 120-ft tower. The motion system includes a beam structure, called the vertical platform, which spans the width of the tower. The vertical platform is mounted on two columns, called equilibrators which extend down into 75-ft deep shafts under the tower floor. Wheel assemblies, which ride along vertical guide rails attached to the tower walls, restrain the vertical platform at both ends and the center of its span.

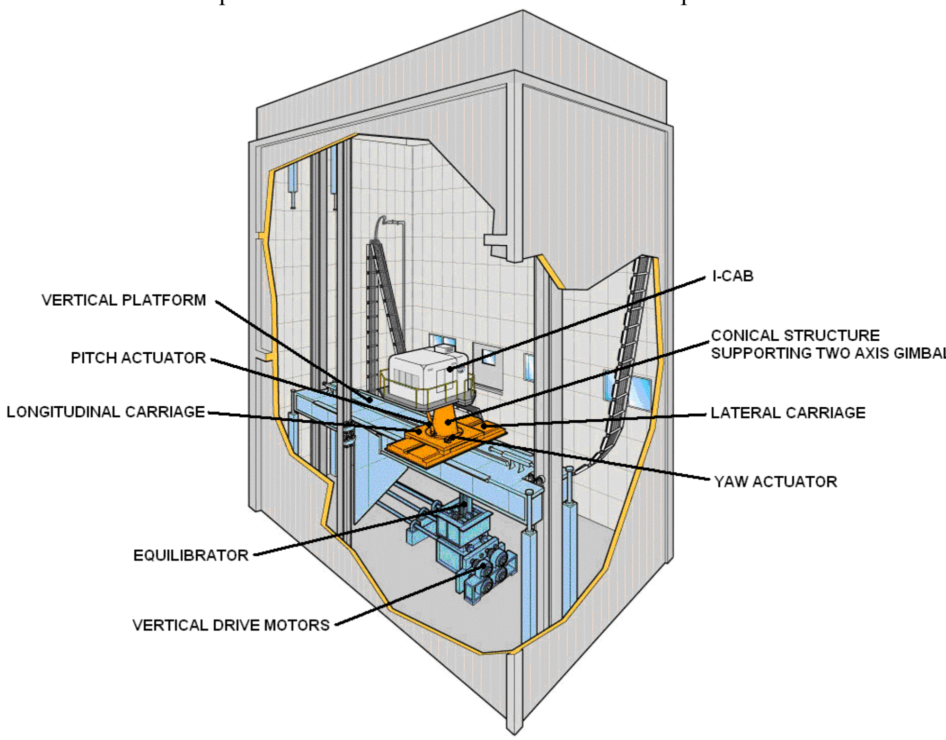

Figure 2. VMS Motion System

The two equilibrators act as pneumatic counterweights. The hollow equilibrator columns slide over inner columns so that the two, along with a gas-tight seal between them, form a cylinder/piston arrangement. Nitrogen gas, supplied by a special storage system, pressurizes the equilibrators such that the pressure forces balance the weight of the 140,000-lb cab and platform structure. This counterbalancing force reduces the power requirement of the vertical drive motors and results in a linear motion response in both directions of vertical travel. An added benefit is that if vertical drive power is lost, the motion system will float to an equilibrium position towards the center of the tower.

Eight mechanically coupled, 150-hp direct-current servomotors power the vertical motion through reduction gearboxes and a rack-and-pinion drive system with the racks mounted on the equilibrator columns (Fig. 2). Four 40-hp direct-current servomotors power the lateral carriage along the vertical platform using reduction gearboxes and a rack-and-pinion drive system with the rack mounted on the top of the vertical platform. A linear hydraulic actuator powers the longitudinal carriage, located atop the lateral carriage.

A 48-inch diameter roller bearing provides the yaw motion, which is mounted on top of longitudinal carriage that is driven by another linear hydraulic actuator. The yaw bearing supports a conical center structure, which has a two-axis gimbal on top that provides roll and pitch motion using two linear hydraulic actuators. A unique feature of the VMS is that the yaw actuator may be attached at two different locations, 90° apart, allowing the longer ±20 ft. translational displacement to be used as either the aircraft's longitudinal or lateral axis, as required for the particular simulation.

B. Motion System Performance

Table 1 summarizes the VMS motion capability. Included are two sets of limits: system limits, that represent the absolute maximum levels attainable under controlled conditions; and operational limits, that represent attainable levels for normal piloted operations. The operational limits listed in Table 1 include the effects of all the system limiters, both hardware and software. The motion system also incorporates a parabolic limiter, which is not reflected explicitly in Table 1. When triggered, the parabolic limiter commands a maximum acceleration opposite to the direction of travel so that the simulator stops just short of a displacement limit.

Table 1. VMS motion system performance limits (from Ref. 3)

Degree of Freedom	Displacement		Velocity		Acceleration	
	System Limits	Operational Limits	System Limits	Operational Limits	System Limits	Operational Limits
Longitudinal	± 4 ft	± 4 ft	± 5 ft/sec	± 4 ft/sec	± 16 ft/sec^2	± 10 ft/sec^2
Lateral	± 20 ft	± 15 ft	± 8 ft/sec	± 8 ft/sec	± 13 ft/sec^2	± 13 ft/sec^2
Vertical	± 30 ft	± 22 ft	± 16 ft/sec	± 15 ft/sec	± 22 ft/sec^2	± 22 ft/sec^2
Roll	± 0.31 rad	± 0.24 rad	± 0.9 rad/sec	± 0.7 rad/sec	± 4 rad/sec^2	± 2 rad/sec^2
Pitch	± 0.31 rad	± 0.24 rad	± 0.9 rad/sec	± 0.7 rad/sec	± 4 rad/sec^2	± 2 rad/sec^2
Yaw	± 0.42 rad	± 0.24 rad	±0.9 rad/sec	± 0.8 rad/sec	± 4 rad/sec^2	± 2 rad/sec^2

The motion drive dynamics may be modeled as equivalent time delays ranging from 90 msec in pitch and roll to approximately 130 msec in the yaw and translational axes (Ref. 4). The VMS motion system includes digital feed-forward compensators (motion lead compensators) in each degree of freedom that may be used to alter and improve the overall motion system dynamics, within limits. The motion lags are typically larger in the translational axes than documented (when they are documented) for small hexapod simulators, which one would expect when considering the relative scale difference between a small hexapod and the VMS. These inherent lags can be effectively eliminated, if a particular task deems it necessary, by modifying the math model so that lags due to actuators and digital effects are removed in exchange for the motion system lag so that the overall equivalent delay in the simulated vehicle is maintained for the evaluation (Ref. 5).

C. Motion Washout Filters

The cockpit motion cueing algorithm uses a high-pass (washout) filter and a rotational/translational cross-feed arrangement shown schematically in Fig. 3. The computed pilot station accelerations of the modeled aircraft are high-pass filtered and attenuated before commanding the motion drive system. Turn coordination and induced acceleration compensation account for the cross-coupled motion commands and provide the correct cues at the pilot's station. A low-pass filter tilts the simulator to provide steady-state longitudinal and lateral acceleration cueing at low frequency (Fig. 3).

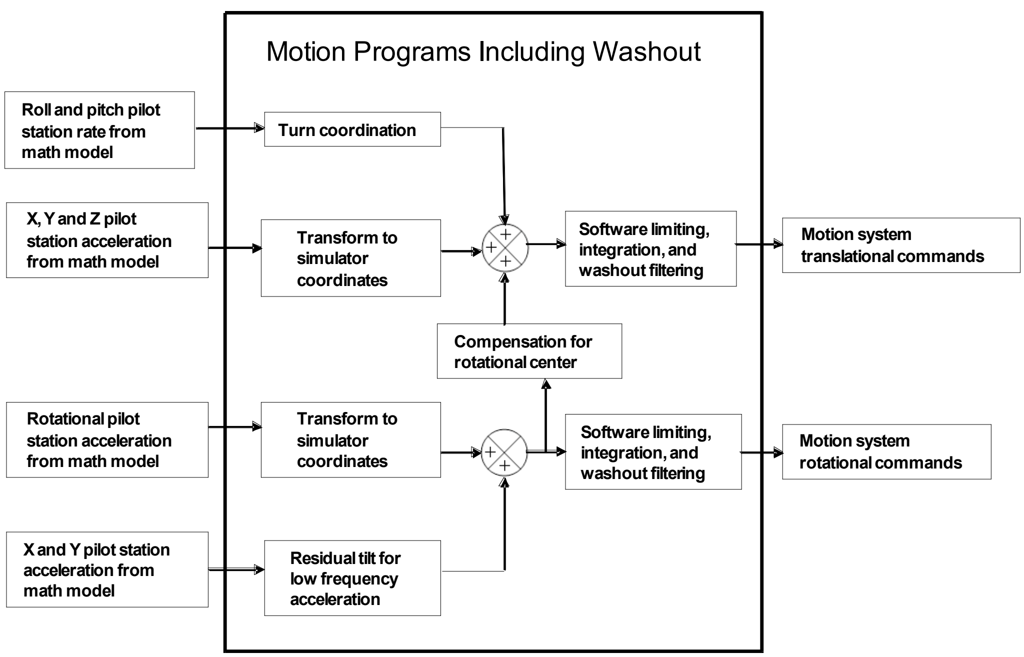

Figure 3. VMS Motion Algorithm Schematic

III. VMS Motion System Design

The design of the VMS is based on the experience gained from a series of ground-based flight simulators at NASA Ames beginning in the late 1940's (Ref. 6). Some key aspects of the VMS motion system design directly trace to the research experience from three past flight simulators at NASA Ames – the sizing of the translational envelope was based on insights gained from the Height Control Test Apparatus (HCTA) and the Flight Simulator for Advanced Aircraft (FSAA), while the equilibrator design was based on experience with the Six-Degree-of-Freedom Motion Simulator (Fig. 4).

The HCTA was a single degree-of-freedom flight simulator with 80 ft. of vertical travel that became operational in 1961. In the early 1970s a study on the HCTA determined the significance of vertical acceleration cues when simulating the visual approach and landing maneuver (Ref. 7). The results indicated that vertical motion cues are important for the landing task, particularly for aircraft with marginal longitudinal handling qualities. The study concluded that a simulator must have a vertical excursion capability of at least ±20 ft. to provide realistic pilot cueing for the approach and landing task. The sizing of the VMS vertical travel envelope was based on this finding.

The FSAA was a six degree-of-freedom flight simulator with ±40 ft. of lateral travel but limited vertical (±4 ft.) and longitudinal (±3.5 ft.) travel. Since its inception in 1969, the FSAA contributed to several important fixed-wing aircraft research programs, but its small vertical travel limited the ability to simulate VTOL aircraft accurately. Similarly, the longitudinal travel was adequate for conventional aircraft, but more travel was needed for simulating the low-speed maneuvers of VTOL aircraft (Ref. 1). A study on the FSAA determined that at least ±16 ft. of lateral travel is required for helicopter flight research (Ref. 8). The sizing of the VMS lateral-travel envelope and the ability to orient the cockpit with either the lateral or longitudinal axis were based on these findings.

The Six DOF Motion Simulator was the first flight simulator to use equilibrators, instead of counterweights to help offset gravitational effects and, thereby, improve vertical dynamic performance (Ref. 6). It became operational in 1964 and had ±9 ft. of travel in all translational axes and ±45 degrees in all rotational axes. Experience with the equilibrators led to the improved design used in the VMS.

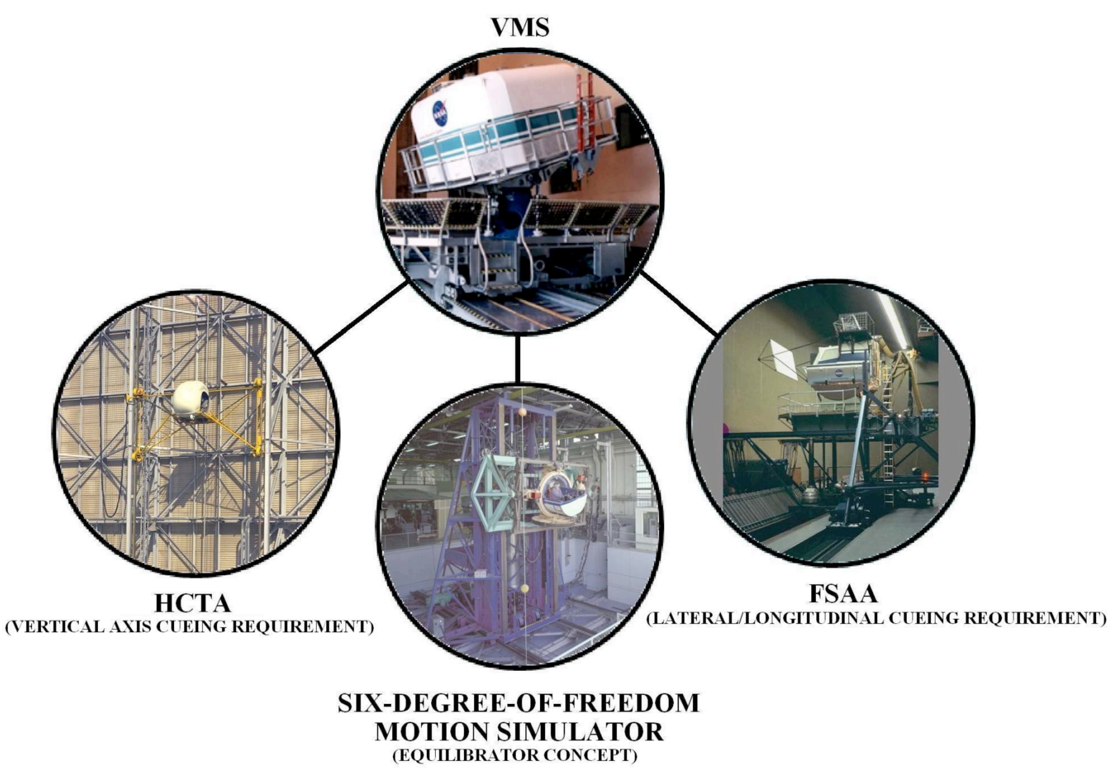

Figure 4. Primary Influences on the VMS Motion System Design

IV. Handling Qualities Studies

In the 1970's, the Army needed a handling qualities specification that could guide the development of rotorcraft that would meet the more demanding missions and tactics envisioned in the future. The military specification for rotorcraft handling qualities, MIL-H-8501A, was written in 1952 and was inadequate (Ref. 9). Several attempts to update MIL-H-8501A met with little success and were not adopted, primarily due to a lack of background data of adequate quality. To overcome the deficiencies in MIL-H-8501A, the Army used Prime Item Development Specifications (PIDS) for procuring new helicopters (Ref. 9). The U. S. Army Aeroflightdynamics Directorate (AFDD), in collaboration with NASA Ames Research Center, began an effort to build a database of handling qualities data and design criteria that could be incorporated into a new handling qualities specification. In 1982, the AFDD began the development of a new rotorcraft handling qualities specification to supersede MIL-H-8501A (Ref. 9). The specification, US Army Aeronautical Design Standard – 33 or ADS-33 (Ref. 10), was completed and published in 1987. Initial development of the specification was for the procurement of the modern light/attack/scout helicopter (LHX) the Army intended to acquire. This program led to the development of a prototype helicopter, the RAH-66 Comanche, but it was subsequently cancelled.

The strategy for developing a helicopter handling qualities database of sufficient quality and validity for use in a military specification was to combine high-fidelity simulation with a limited amount of flight test activity. Almost all the simulation data incorporated into ADS-33 came from VMS studies. The process of developing the database is ongoing with future studies filling known gaps in the database and refining others. Table 2 lists the VMS simulation studies that have supported this process thus far.

Reference 1 contains a comprehensive summary of the rotorcraft research conducted in the VMS in its first decade of operation. Initial studies focused on two issues of primary concern: 1) rotorcraft design requirements for low-altitude or nap-of-the-earth (NOE) flight, and 2) flight in adverse visual conditions. Not all these studies were documented or published, but their data were used to develop criteria in ADS-33 and are available in the Background Information and Users Guide to ADS-33 (Ref. 10).

Table 2. Rotorcraft handling qualities simulation studies

Simulation Description	***Year(s)***
Heavy-Lift Rotorcraft (HLR) stability margin/handling qualities	2008
Handling qualities with external slung loads (8 simulations)	1994 – 2008
Civil handling qualities specification	2001
LHX/RAH 66 handling qualities (4 simulations)	1982 – 1992
Helicopter cross-coupling studies (3 simulations)	1986 – 1994
Handling qualities for helicopter air combat (6 simulations)	1984 – 1992
Handling qualities for yaw control	1984
Handling qualities for roll control (2 simulations)	1984, 1985
Single/dual pilot advanced cockpit and handling qualities (2 simulations)	1986
Handling qualities for shipboard landing	1984
Handling qualities for vertical control	1983-1984
Effect of rotorcraft design on handling qualities (3 simulations)	1980-1982

Initial studies investigated the effect of design variations on rotorcraft dynamic characteristics and handling qualities. These included the effect of vertical damping and thrust available (Ref. 11), pitch/roll and collective/yaw cross coupling (Refs. 12 and 13), yaw control (Refs. 14 and 15), and roll control (Ref. 16). Other studies investigated some of the fundamental precepts being developed for the specification – required response type and bandwidth. An innovative concept introduced in ADS-33 is the trade-off between augmentation (which defines response type) and the visual cueing environment. Ground-based and in-flight simulation studies established that when the visual cueing environment is degraded, increased compensation is required to maintain handling qualities at a satisfactory level. Bandwidth is a measure that defines the quickness in the response to control inputs and represented a shift, at the time, from time-domain based performance criteria to a more accurate and discriminating frequency-domain measure. Studies on the VMS that developed these concepts include those reported in Refs. 17, 18, and 19.

Several studies by the AFDD also investigated helicopter and flight control system design requirements for aggressive air-to-air combat (Refs. 20, 21, and 22) at low-altitude. These studies provided data on the effect of response type, pitch/roll/yaw bandwidth, and turn coordination on handling qualities when the rotorcraft itself is used as a pointing platform. Another study investigated the yaw dynamic requirements for a rotorcraft with a turreted gun engaged in low-level air combat operations (Ref. 23). The study investigated the potential trade-off between gun slewing angular movement capability and required rotorcraft yaw axis response. A separate series of studies investigated the handling qualities and cockpit interface that would be required for single-pilot operation envisioned, at that time, for the LHX program (Ref. 24). These studies indicated that the mission management and demanding NOE flight environment placed an unacceptable workload on a single pilot that may be alleviated by increasing augmentation through the flight control system.

An important outcome of these studies was the progressive development of evaluation tasks that were designed to be representative of the mission tasks expected of rotorcraft but also constrained to allow repeatability and promote consistency in handling qualities ratings. These evaluation tasks, or Mission Task Elements (MTEs), were refined over the course of many experiments on the VMS and included in ADS-33 as demonstration maneuvers for evaluating the overall handling qualities of a rotorcraft. Task performance displays for the MTEs were also developed over the course of many experiments on the VMS and these displays have transitioned to flight testing.

Finally, a series of eight simulation studies investigated the effect of externally slung loads on helicopter handling qualities. The results of the first five simulation studies by the AFDD are reported in Ref. 25. These simulation studies established a database of handling qualities data for future inclusion in ADS-33 as guidelines for designing rotorcraft that carry external loads. The database on handling qualities will be further expanded by follow-on simulation studies on the VMS to explore heavy cargo rotorcraft operations including the effect of pitch/roll response-type on handling qualities with slung loads.

Since its release, ADS-33 has guided the procurement of the CH-47F and CH-53K helicopters, and the UH-60Mu and AH-64D fly-by-wire upgrades by the Army and Navy. It was designed for, and used as, the guiding specification for the RAH-66 Comanche flight control system that is the basis for the full-authority fly-by-wire flight control systems implemented on the UH-60Mu, CH-53K, H-92 Superhawk, and the digital automatic flight control system (DAFCS) on the CH-47F. (The CH-47F flight control system was evaluated on the VMS.) The RAH-66 control system design was, in turn, based on extensive research on the Army's advanced digital optical control system (ADOCS) program that also used the VMS for initial design and development.

V. Flight Control Design Studies

Table 3 lists the VMS simulation studies that evaluated flight control system concepts and designs. All these development efforts were closely linked with the development of a handling qualities database. To evaluate new flight control concepts in preparation for the procurement of a new attack helicopter (LHX), the Army initiated the ADOCS program to investigate modern flight control system concepts and pilot-vehicle interfaces. A series of simulation studies on the VMS evaluated modern control laws, flight control system architectures, and cockpit interface concepts including multi-axis side sticks and advanced pilot displays (Ref. 26). Outcomes of these studies were recommendations for the design of multiaxis pilot controllers, flight control system designs with advanced response types; control law mode switching logic; automatic stick force trimming; and helmet mounted display. These concepts were implemented and flight-tested on the ADOCS UH-60 helicopter. The designs translated well from simulation to flight and only minor parametric changes were required in flight to optimize handling qualities (Ref. 27). The program provided invaluable data on advanced flight control system design. The fundamental flight control concepts and architectures developed in the program have influenced all the rotorcraft fly-by-wire flight control systems designed since that time.

Table 3. Flight control systems research simulations

Simulation Description	*Year(s)*
CH-47F digital automatic flight control system (2 simulations)	2004 - 2005
UH-60 MCLAWS evaluation	2002
Partial authority flight control systems (4 simulations)	1991 - 1998
Advanced Digital Optical Control System (ADOCS) program (4 simulations)	1981 - 1985

The difficulty of landing rotorcraft in blowing sand, known as brownout, became evident in the first Gulf War. Conducting operations under cover of darkness using night vision goggles (NVG) was also becoming more prevalent as the quality of the devices improved. At that time, there was significant evidence that control augmentation could alleviate handling qualities deficiencies in degraded visual environments such as brownout and NVGs. A series of simulation studies on the VMS investigated the possibility of modifying the existing limited authority flight control system on the UH-60 Black Hawk to provide added augmentation to improve handling qualities when flying in degraded visual environments (Refs. 28 - 30). The simulation studies explored different methods for adding this increased augmentation to the existing Black Hawk flight control system and evaluated the effect of saturating the stability augmentation system for larger pilot inputs. Based on the favorable results of these studies, increased augmentation was proposed for the Black Hawk and tested on the VMS (Ref. 31).

The CH-47F with its digital automatic flight control system (DAFCS) was the first production Army helicopter acquired using ADS-33 requirements. The DAFCS included advanced response types to improve handing qualities in degraded visual environments. Following development and initial testing by the manufacturer, the system was refined and evaluated by Army pilots on the VMS (Ref. 32). The simulation investigations showed that the DAFCS significantly improved handling qualities in day and night (using NVGs) visual conditions when compared with a CH-47D. Findings from the VMS study also led to improvements in mode transitions between response types in the DAFCS.

VI. Studies on Specific Rotorcraft Programs

The high-fidelity simulation capability of the VMS was used to evaluate and test new rotorcraft concepts and configurations such as tilt-wing and tilt-rotor as well as to support existing programs such as Comanche and Apache by implementing and evaluating simulation models (Ref. 5). Table 4 lists the simulation studies that fall in this category.

Other programs include several unique rotorcraft configurations including a tilt-wing, X-wing, and the Piasecki Vectored Thrust Combat Agility Design (VTCAD). The tilt-wing studies ranged over a period of 10 years and investigated novel control methods such as the geared flap, that were necessary to control the aircraft during wing tilt (Ref. 35), and the effect of augmentation on handling qualities during approach and landing (Ref. 36). The VTCAD concept involved the substitution of a ducted fan with thrust vectoring capability in lieu of a tail rotor on an AH-64 helicopter to increase its speed and agility. The AFDD evaluated the efficacy of this design in two VMS investigations.

The X-wing program was a joint Army/NASA project to investigate high-speed rotorcraft that culminated in the development of the prototype Rotor Systems Research Aircraft (RSRA) to test rotor and propulsion concepts. The complex fly-by-wire flight control system for the X-wing required control transitions as the aircraft transitioned from a rotorcraft to a fixed-wing aircraft (Ref. 37). These control laws were refined and evaluated on the VMS.

Table 4. Simulation studies supporting specific rotorcraft programs

Simulation Description	***Year(s)***
RASCAL safety systems (3 simulations)	1989 - 2008
Joint Shipboard Helicopter Integration Process (JSHIP) (2 simulations)	2000 – 2001
RAH-66 Comanche	1997
Tilt-Wing/Advanced Theater Transport (ATT) (4 simulations)	1991 – 2002
Variable Diameter Tilt Rotor (VDTR)	1996
AH-64 Apache (4 simulations)	1988 – 1993
Piasecki VTCAD (2 simulations)	1991 - 1993
X-Wing/RSRA (4 simulations)	1984 - 1987
SH-2F	1982

A joint NASA/Sikorsky study on the VMS compared Sikorsky's Variable Diameter Tilt Rotor (VDTR) concept with a conventional fixed diameter tilt-rotor (Ref. 38). Pilots from government and industry evaluated the VDTR in regular and emergency (engine failure) operations. The study demonstrated the enhanced performance potential of the VDTR and identified areas for further study.

Several simulation studies also supported the initial development of the Army/NASA Rotorcraft variable stability Black Hawk known as the Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL). RASCAL is operated by the U.S. Army's Aeroflightdynamics Directorate. A particular concern during development was controllability of the helicopter if there was a failure in the research flight control system that operated in parallel with the production flight control system. Several studies investigated and quantified the effect of failure transients and assessed the handling qualities following a failure (Ref. 39) and evaluated RASCAL safety systems. A pilot failure rating scale was developed to assess the safety and handling qualities requirements associated with dynamic failures that could occur on a full-authority flight control system as envisioned for RASCAL (Ref. 40). Recent studies on the VMS focused on modifying the RASCAL safety systems to allow flight testing at lower altitudes.

VII. Simulation Fidelity Studies

A host of experiments aimed at understanding simulation fidelity requirements for helicopters were performed on the VMS since its inception including those listed in Table 5. Since the VMS represented the most capable simulator in the world, the first natural question to ask was how good is it compared to flight. While answering critical questions necessary for advancing simulation-based flight training, the results of these studies were also fundamental to the validity of the studies conducted in the other streams of research outlined in this paper.

The first attempt to compare how well the VMS could simulate helicopter flight was conducted cooperatively among several organizations (Ref. 41). Pilot opinion (HQRs) were Level 1 in flight but Level 2 in simulation. These differences led to investigations to improve the rotor model, servo dynamics, and engine. Improvements to the math model, visual systems, motion configurations, and experimental tasks and protocols led to experiments documented in Ref. 42. This experiment compared performance and pilot opinion using a UH-60 operated out of NASA Ames. Extensive frequency-domain identification compared the simulation performance with flight, with the conclusion that the model was a reasonable representation of the flight vehicle. This was an improvement from the 1984 simulation study but deficiencies in visual and heave motion fidelity were noted.

Table 5. Simulation fidelity research

Simulation Description	*Year(s)*
Visual scene height perception - PsychoPath (2 simulations)	2001 - 2006
Autorotation Cues – AutoCue (2 simulations)	2000 – 2001
Computation situational awareness model -- SAMSIM	2000
Simulation fidelity requirements (7 simulations)	1996 – 1999
Motion and visual evaluation – MOTIVE	1993
Simulation validation – SIMVAL (3 simulations)	1990 – 1993
Visual/motion synchronization – VISMOSYNC (2 simulations)	1990 – 1992
Visual and motion delay - SIMVAC	1992
Blackhawk validation	1989
Simulator sickness study	1989
Helicopter autorotation (2 simulations)	1984 – 1985

Early research on the VMS showed how far away the simulated cues in a typical helicopter are from the real world (Ref. 43) and exposed the need for systematic investigations with objective measures to determine fidelity requirements. Early emphasis was on the relative timing between the visual and motion cues that was a suspected cause of simulator sickness. Using four different motion conditions, McCauley (Ref. 44) found that simulator sickness increased with both time and the level of maneuvering. Using a UH-60 model, Sharkey (Ref. 45) subsequently found that false motion cues had an adverse effect similar to having no motion cues at all.

The effects of asynchrony in the motion and visual cues were also investigated for handling qualities effects. Mitchell and Hart (Ref. 4) examined variations in visual time delays and motion washout filters. They suggested tailoring the motion system to the task and minimizing the mismatch between motion and visual delays. Chung and Schroeder (Ref. 46) studied the motion and visual synchrony among roll, and lateral axes using a predominantly lateral axis task and recommended that the equivalent time delay mismatch between the roll and lateral motion cues not exceed 40 msec. Their work also suggested that the equivalent delays in the motion cuing could exceed the equivalent visual delay without a resulting degradation in handling qualities ratings.

When simulating motion in a ground-based simulator where motion displacement is limited, there is a necessary trade-off between the desired initial, or short-term acceleration and the desired sustaining, or long-term, acceleration. Mitchell (Ref. 47) showed that the addition of motion improved pilot opinion ranging from ½ to 2 HQR points. For precision tasks, sustained acceleration cues were preferred (reduced washout natural frequencies of the motion filter), while, for aggressive tasks, short-term acceleration cues were preferred.

Schroeder (Ref. 48) used pilot describing function measurements to examine a variety of motion gains and motion washout filter variations on a classical single-axis compensatory tracking task. The results showed that motion cues allowed the pilot to generate lead compensation and improve target tracking phase margins with increasing filter gain or decreased natural frequency. The study also showed no effects for any of the pure yaw motion configurations, which led to subsequent investigations.

To help answer the question on what characteristics a motion filter should have so that simulation is a reasonable representation of flight, Schroeder (Ref. 49) evaluated the proposed Sinacori motion fidelity criteria (Ref. 8). Objective and subjective results showed that the original criteria could be relaxed, and these criteria (shown in Fig. 5) are still used today as a guide when configuring the VMS motion system as well as other simulators. When compared against these criteria, the gain and phase mismatch for the VMS motion system spans the "like flight" and "different from flight" regions, depending on how the motion filter settings are optimized (Fig. 5).

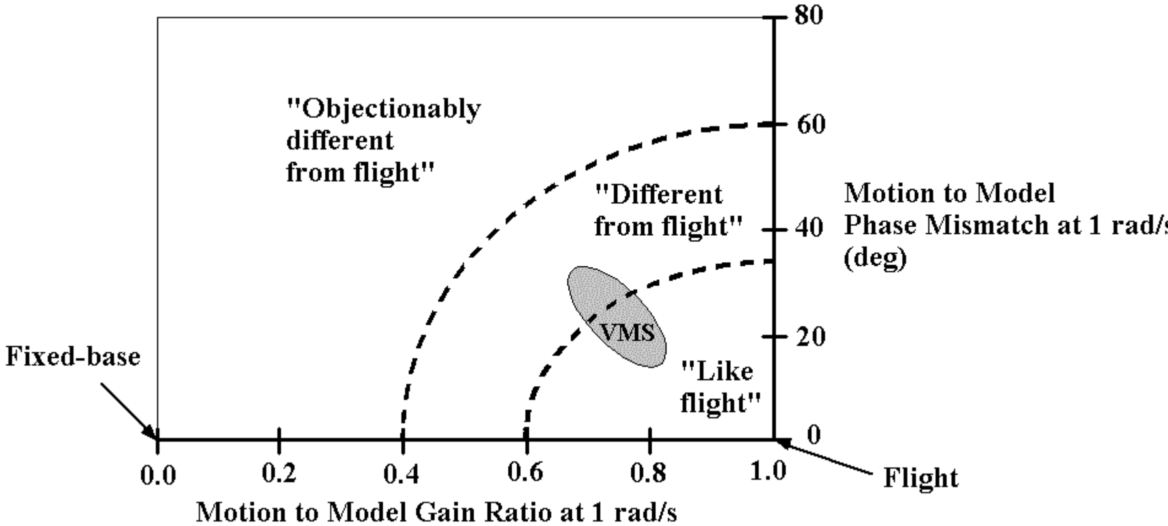

Figure 5. Motion Fidelity Criteria

A question that often arises when configuring the motion system is the level of fidelity required in each axis. Specifically, the earlier study that showed little effect of yaw cueing led to a more detailed study (Ref. 50). This study evaluated a helicopter in a single degree of freedom hovering yaw task. Four variations in the motion cueing were studied: full motion, only lateral translational motion, only yaw rotational motion, and no motion. The study found that the lateral acceleration cue was of predominant importance in both performance and opinion. This suggested that if you had strong lateral translational cues, then the yaw rotational cues might be redundant and unnecessary.

In a study that considered visual cueing aspects as well as motion, Johnson (Ref. 51) investigated how the displayed level-of-detail changes as one gets closer or further away from an object for a height control task. The results showed that changing the level-of-detail to maintain constant optical density as the altitude changed, like that of the real world, improved altitude awareness. Texture at this time was only beginning to be used in the VMS. Separately, adding platform motion improved speed regulation and altitude perception. Further systematic changes in visual scene, via changing spatial frequency with alternating black-and-white stripes, and motion cues were evaluated in the vertical axis (Ref. 52). The variations in visual scene evaluated had no effect, while the motion configurations did have an effect. These configurations were subsequently analyzed using a structural pilot model (Ref. 53). The intent was to develop and calibrate a model that would predict pilot opinion for a given rotorcraft and task, and the model's predictions correlated well, in a ranking sense, with the subjective ratings.

The VMS was used to evaluate cueing effects on autorotation in two studies separated by more than a decade (Refs. 54 and 55). In the first study, autorotation task performance decreased with degraded motion cues, yet acceptable performance could be attained as long as there were adequate visual cues. With improved visual cueing technology, the second study evaluated the effect of visual texture and motion variations on autorotation task performance. Visual texture affected all measures, but the finest texture did not perform the best, debunking a myth that more texture is better. This result was also supported by a fixed-base psychophysics study (Ref. 56). Visual detail affected only pilot subjective opinion. Pilot performance as well as opinion of motion fidelity improved with increased motion cueing.

VIII. Guidance and Display Studies

The high-level of motion and cockpit fidelity offered by the VMS made it an ideal platform to assess and prototype rotorcraft guidance and display concepts (Table 6). Early studies on the VMS evaluated the rotorcraft handling characteristics necessary for low-level nap-of-the-earth missions envisioned for the next generation of military rotorcraft. These studies showed that the workload for such missions was unacceptable for a single pilot. A series of studies over several years beginning in 1988 conducted research to develop an automated helicopter flight capability for potential application in the U.S. Army light, attack, scout helicopter (LHX) program (Fig. 6). Several simulation studies on the VMS developed and refined the critical components of a guidance system for terrain and obstacle detection, path prediction, guidance displays and symbology, and automatic control concepts for terrain following/terrain avoidance (TF/TA) (Refs. 57, 58, and 59). The resulting guidance system was implemented on the Army's UH-60 System Testbed for Avionics Research (STAR) and tested in flight. The outcome of the project included several fundamental concepts for displaying flight information superimposed on sensor imagery.

Another series of studies by the AFDD investigated methods for predicting helicopter maneuver limits and communicating this information to the pilot via tactile cueing through the pilot inceptor (Ref. 60). The results showed that tactile cueing through a conventional inceptor or a sidestick enabled the pilots to easily track helicopter structural and power-train limits and avoid exceedances while maneuvering aggressively without referring to flight instruments. The cueing allowed the pilots to extract maximum maneuvering performance from the helicopter without risk of damage. This technology was developed for testing on an AH-64 Apache helicopter under the Army's Helicopter Active Control Technology program (Ref. 61).

Table 6. Research into guidance and display concepts

Simulation Description	***Year(s)***
Brownout symbology simulation	2007
Manned-unmanned Teaming - MUT	2007
Comanche HMD	2002
Helicopter maneuver envelope enhancement (5 simulations)	1996 - 1997
Technical control panel – TTCP (2 simulations)	1993
Automated nap-of-the-earth – ANOE (4 simulations)	1989 - 1996
Cat A terminal area procedures (2 simulations)	1994 - 1995
Terrain following/terrain avoidance – TFTA (4 simulations)	1988 - 1992
HUD-3D, ESPNVS, flight symbology	1989 - 1991

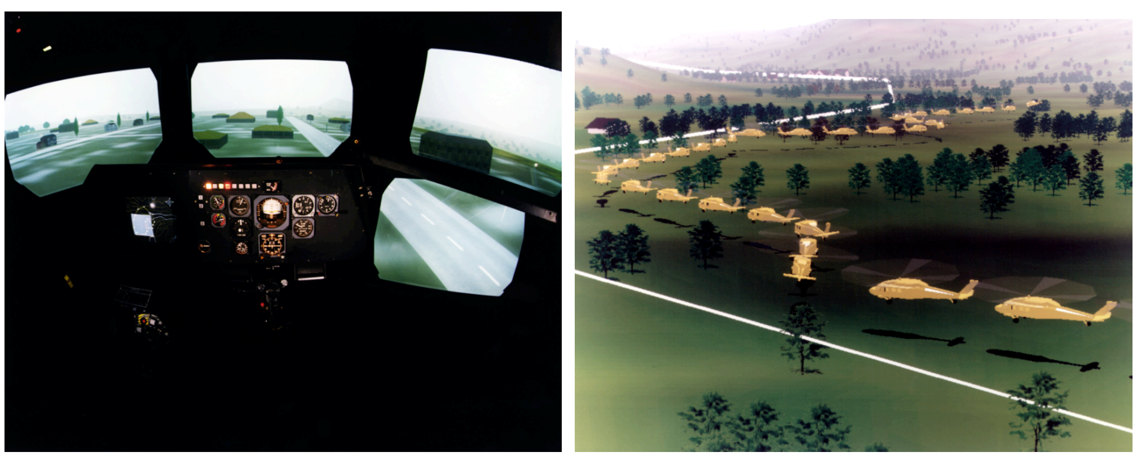

Figure 6. Automated NOE cockpit and test course

The increased operation of helicopters in urban areas brought with it the risk of an accident, particularly in an emergency situation such as an engine failure. Updated procedures for recovering from an engine failure when taking off or landing in confined areas were needed. Two simulation studies on the VMS by NASA and the FAA investigated methods to reduce pilot workload and increase safety for rotorcraft terminal area operations (Ref. 62). The studies examined the benefits of optimal procedures, cockpit displays, and alternate cueing methods for safe terminal area procedures with one-engine inoperative. Results showed that an integrated display reduced pilot workload and improved safety when compared with conventional instruments.

In the area of head-mounted displays, a study on the VMS investigated the handling qualities benefits that could be realized using new display law design methods for hover displays (Ref. 63). The display law design was applied to the Apache helmet-mounted display format, using the Apache vehicle dynamics to tailor the dynamics of the velocity predictor symbol. The new symbol dynamics improved the pilots' ability to maneuver about hover in poor visual cuing environments and improved pilot opinion. More recently, the AFDD conducted a simulation study to examine the performance of the Comanche Contact Analog world-referenced symbology displayed on the Comanche's helmet-mounted display when compared with a compressed symbology design similar to that specified by the former MIL-STD-1295 (Ref. 64). Pilot opinion showed a preference for the MIL-STD-1295 symbology. The study recommended specific improvements to the Contact Analog symbology. Another AFDD study, reported in Ref. 65, examined ways to optimize the alerting effectiveness of helmet display symbology. The research investigated two approaches to increasing the effectiveness of alerts – using the entire display surface and including information about the required response in the alert itself. Helmet display symbology was based on the AH-64's pilot night vision system (PNVS), cruise mode symbology. The data showed a small benefit from both the full-screen alert and the partial information alert.

IX. Tilt-Rotor Studies

In 1981 the Deputy Secretary of Defense directed that the services reviewed V/STOL technology with the intent of establishing a joint rotary wing aircraft development program to satisfy service lift requirements for medium lift V/STOL aircraft in the 1990s and beyond. This would take advantage of the advanced, but mature, tilt-rotor technology already in place by the early 1970s. The joint NASA/Army XV-15 Tilt-Rotor Research Aircraft program had already begun in the early 1970's and became the foundation for the full-scale development of the JVX, later designated as the V-22 Osprey. A number of simulation studies conducted at the VMS from 1980 to 1985 validated the JVX math model and evaluated the flight control system characteristics. Previous studies on the FSAA had led to the evaluation and selection of Bell to build the XV-15 prototype.

The continued development and flight-testing of the military V-22 Osprey prepared the way for the introduction of a civil tilt-rotor transport. The potential introduction of a civil tilt-rotor transport into the National Airspace System presented challenges and opportunities for vertical flight solutions to airspace congestion. The Federal Aviation Administration (FAA) had developed a Vertiport design guide based on helicopter capabilities and projected civil tilt-rotor transport performance. As a complement to the FAA guide, NASA undertook an effort to develop controls and display technology to fully utilize the capability of this rotorcraft. This effort took the form of a series of ten piloted simulation studies conducted at the VMS (from 1988 to 2001) to investigate tilt-rotor terminal operations and certification issues (Fig. 7). The general objectives of these simulation studies were: 1) to develop design guidance for safe, all-weather, low-noise flight operations, 2) to develop controls and cockpit displays to support tilt-rotor transport operations, and 3) to develop tilt-rotor transport terminal area procedures. All these objectives were met.

Initial studies evaluated steep instrument (IFR) approaches to confined spaces. These steep approaches would reduce the required obstruction-free approach zone and could significantly reduce the noise footprint of terminal operations. The studies investigated two display concepts to provide guidance for steep IFR approaches (Refs. 66 and 67) with glide slopes ranging from the nominal 3-degrees up to 25-degrees. The next series of experiments further evaluated these steep IFR approaches under One-Engine-Inoperative (OEI) conditions. This was followed by handling qualities evaluations of noise abatement landing approaches and comparing them with acoustic measurements from flight tests using the XV-15 aircraft flying similar trajectories (Ref. 68). A potential two-segment approach with initial deceleration at a three-degree glide slope converting to final approach along a nine-degree glide slope was also investigated. The final experiments were full mission simulation studies that evaluated operation in congested airspace and led to the development and use of pursuit displays, particularly for the transition from the airplane type cruise configuration to the helicopter configuration for final approach and landing (Refs. 69 and 70).

In another study, NASA evaluated the effectiveness of the V-22 Osprey tilt-rotor in one-on-one air combat maneuvering on the VMS, for the Marine Corps (Ref. 71). The study showed that the unique speed and maneuvering characteristics of the V-22 enhanced its survivability against both fixed-wing and rotorcraft aggressors.

Figure 7. Civil tilt-rotor cockpit (with HUD) and typical visual scene

X. Concluding Remarks

Over the past three decades, the NASA Vertical Motion Simulator has provided a wealth of data and knowledge to further rotorcraft technology and safety. The collaboration between NASA and the Army Aeroflightdynamics Directorate at the Ames Research Center has been, and continues to be, a primary reason for the prolific output of valuable research from this facility. This collaboration has developed a database of knowledge on a variety of interacting disciplines on rotorcraft including handling qualities, simulation fidelity, guidance and displays, and design. This database is now used in military procurement and in civil applications on training simulation and guidance displays. NASA programs as well as those in collaboration with the FAA have also contributed significantly to the development of the tilt-rotor aircraft and its civil derivative. Specific contributions include:

- Data on rotorcraft handling qualities that formed a basis for the current military specification on rotorcraft handling qualities, ADS-33E;
- Understanding on human motion and visual cueing, and developing guidelines for configuring simulation cueing environments;
- Designing and evaluating novel rotorcraft configurations including the tilt-wing and tilt-rotor;
- Designing and evaluating production flight control systems including the CH-47F;
- Designing and evaluating rotorcraft guidance and display concepts for low-level terrain following and helmet-mounted displays; and
- Civil tilt rotor operation and certification.

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