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The NASA Ames Vertical Motion Simulator – A Facility Engineered for Realism

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Abstract:

Developed initially to provide the motion fidelity necessary for research on vertical and short take-off and landing aircraft, the Vertical Motion Simulator at NASA Ames Research Center, provides the realistic pilot cues necessary for conducting research on a wide variety of vehicles with challenging stability and control characteristics. Its design and development leveraged prior experience with motion-based simulators at Ames to optimize the motion cueing environment to ensure the delivery of high quality research data that translates to flight. Over 30 years of continuous operation, the Vertical Motion Simulator has contributed significantly to the body of knowledge in a range of disciplines including human pilot cueing modalities and simulation fidelity, aircraft/spacecraft handling qualities and flight control design, and pilot-vehicle interface design. These contributions directly benefited several aerospace programs and flight safety, particularly the design and development of flight control systems for modern rotorcraft, the Joint Strike Fighter, and the Space Shuttle Orbiter. Its overall level of realism makes it a viable surrogate to flight-testing and a safe and cost-effective solution for reducing risk in aerospace vehicle development programs and investigating fundamental pilot-vehicle interaction issues.

Introduction:

The 1960s and 70s witnessed an expansion in the capabilities and mission requirements of rotorcraft and the introduction of jet-powered vertical and short take-off and landing (VSTOL) aircraft. The ability to hover and maneuver precisely at low-speed and then transition to high-speed flight made them useful for a variety of missions that could not be fulfilled by conventional fixed-wing aircraft. These aircraft, however, presented an unique set of pilot-vehicle interface challenges not seen in conventional fixed-wing aircraft: 1) unfavorable stability and control characteristics at low-speed and hover; and 2) static and dynamic behavior that changed significantly in a relatively small speed range during transitions to high speed flight. Advancing the capabilities of VSTOL aircraft demanded that these challenges be properly understood and overcome, and this required a simulation environment that could recreate the pilot feedback cueing available in an actual aircraft. The Vertical Motion Simulator (VMS) at NASA Ames Research Center was engineered to provide the realistic pilot cueing environment necessary to be a viable surrogate to flight test research for evaluating VSTOL aircraft and other future aircraft concepts.

The VMS became operational in 1979 and incorporated the largest and most realistic motion system in the world, a distinction it holds to this day. The high-fidelity independent rotational and translational motion displacements are combined with an interchangeable cab system housing realistic computer-generated visual displays of the outside world and adaptable cockpit interfaces with accurate control-feel systems, flight instruments and displays. These features make the VMS an extremely adaptable and efficient platform for studying all types of aircraft with widely varying and challenging flight dynamics and performance issues, as well as pilot-vehicle interface concepts. Its large motion capability made it ideally suited to investigating pilot-vehicle interactions and interfaces, because the high-fidelity motion cueing increased the likelihood that the research findings would translate to a flight environment.

Over the past three decades, the VMS has made significant contributions to aeronautical research in the broad area of pilot-vehicle interaction for a range of existing and conceptual aircraft, both fixed and rotary-wing. With its unparalleled level of fidelity, the VMS was also ideally suited to fundamental research on pilot cueing and simulation fidelity. Concurrent and interacting studies, therefore, used the VMS's unmatched six degree-of-freedom motion capability to examine human pilot cueing and the level of simulation fidelity required to accurately recreate the pilot-vehicle interaction observed in flight. Other

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studies on the VMS over the years included handling qualities evaluations of aircraft concepts with unconventional and challenging flight characteristics (e.g., Space Shuttle Orbiter, high-speed civil transports, large fixed-wing transports, tilt-wing, tilt-rotor, etc), flight control design and handling qualities assessment of production aircraft (e.g., C-17A, CH-47F, and UH-60), pilot guidance and cueing display design and development, and accident investigations (e.g., USAir 427, and AA 587). Recent studies on the VMS are evaluating the handling qualities and flight control system requirements for the next generation of US spacecraft – the Orion Crew Exploration Vehicle and the Altair Lunar Lander vehicle.

This paper describes the VMS and its motion characteristics and summarizes its contributions and impact on aeronautics research. A detailed facility description emphasizing the motion system is provided followed by a description of the prior simulation experience that influenced the design of the VMS motion system. This is followed by a summary of the research conducted on the VMS through its history and its impact on aircraft programs and projects. As complete coverage of all vehicles simulated in the history of the VMS is prohibitive in scope, this paper focuses on simulation fidelity and cueing, VSTOL research, and Space Shuttle development and training that comprise the majority of the simulations conducted on the VMS.

VMS Facility Description

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 for tailoring the cockpit 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. 1). 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 the simultaneous conduct of up to three different simulation experiments in the facility. In-house graphics expertise customizes 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.

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. 2). 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.

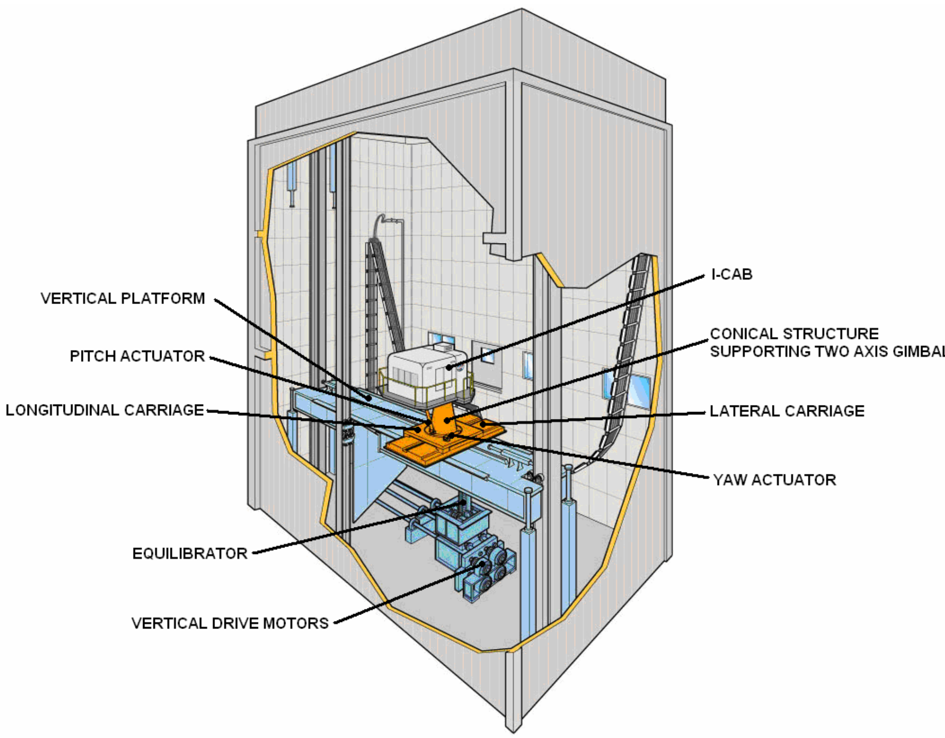

Figure 2. VMS Motion System

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 for the large ±20 ft. of translational displacement in either the aircraft's longitudinal or lateral axis, as desired by the particular simulation.

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. 2)

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. 3). 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. 4).

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).

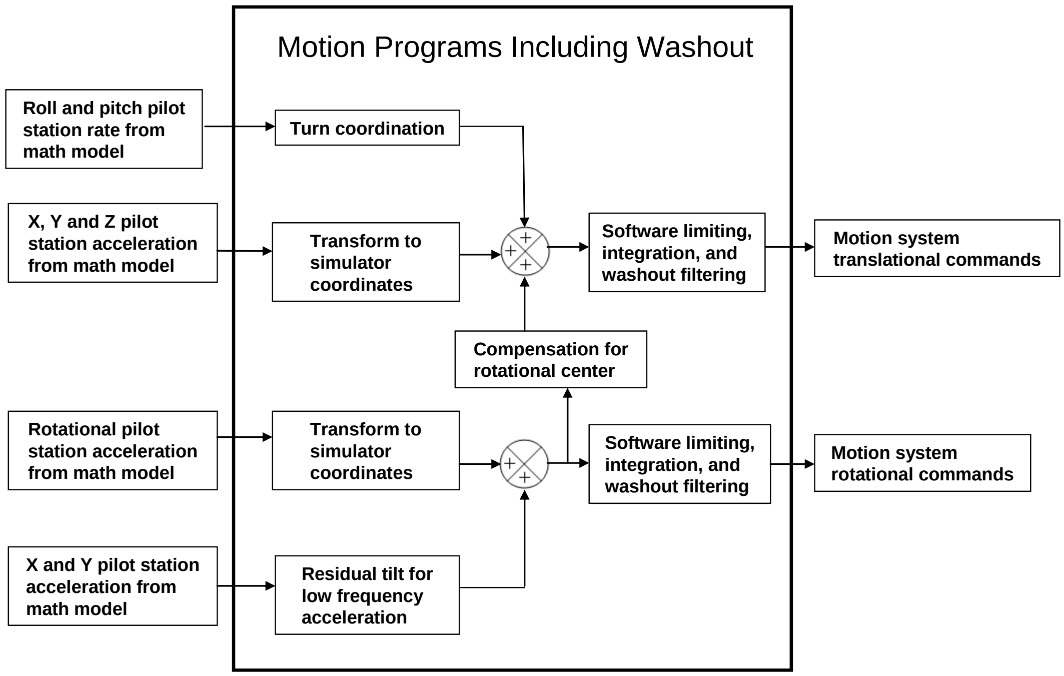

Figure 3. VMS Motion Algorithm Schematic

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. 5). 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. 6). 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 these findings.

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. A study on the FSAA to determine motion simulation requirements for helicopter flight research determined that at least ±16 ft. of lateral travel is required (Ref. 7). 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. 5). 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.

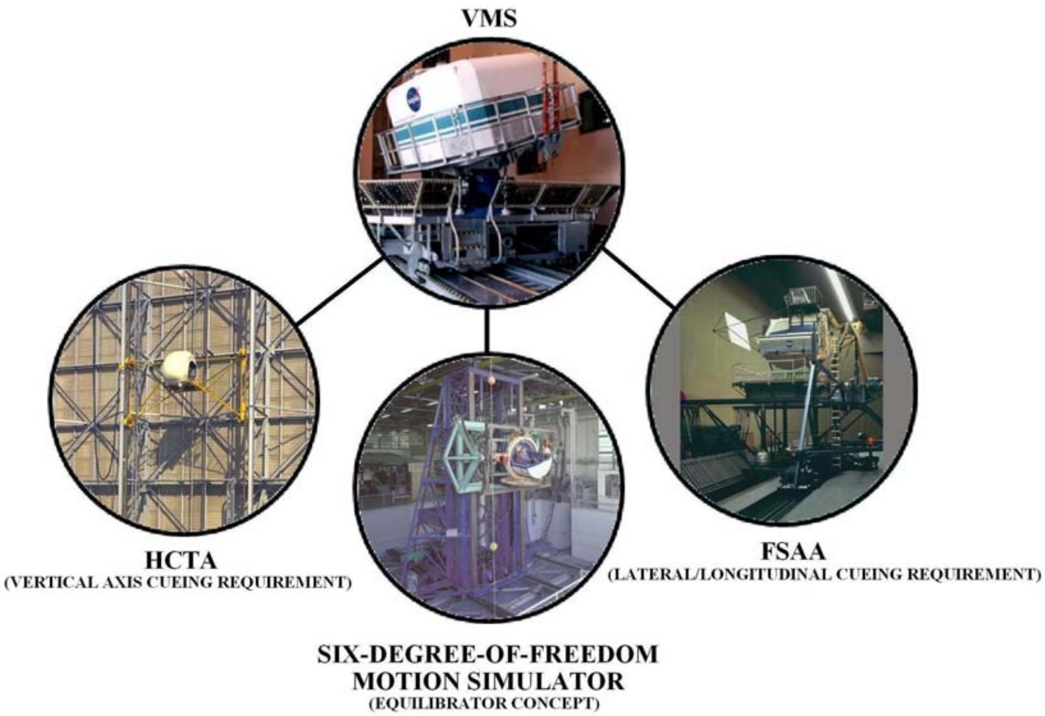

Figure 4. Primary Influences on the VMS Motion System Design

Simulation Fidelity Studies in the VMS

A host of experiments aimed at understanding simulation fidelity requirements for aircraft have been performed on the VMS since its inception. Given its one-of-a-kind capabilities, the first natural question to ask was “how good is it compared to flight?” Initial answers to that question used a model of a UH-60 and identified deficiencies in all of the components that supply the cues: the math model, the inceptors, the visuals, and the motion. While the gap in these components continued to taper relative to flight, more general studies investigated cuing requirements. Given the motion envelope of the VMS, predominant emphasis was placed on motion cues. These studies led to the validation and use of motion fidelity criteria.

As technology improved, the cueing investigations became more detailed, especially as the interactions between the motion fidelity and visual requirements were considered. For instance, rudimentary orthogonal grids composed of lines were previously used to artificially convey visual feedback of positions, orientation, and rates. Even as texture and increasing levels of detail were introduced, the visual cueing was still deemed inadequate, so questions were raised on visual requirements.

Another byproduct of the technology improvements was the hopefulness that simulators could be used to effectively simulate difficult tasks such as autorotation and shipboard landing. Since these tasks place stringent cueing demands on simulation, the cueing studies that had been performed to date were valuable.

The VMS studies described next encompass various questions that have been posed on motion fidelity, visual cueing, and the ever-hopeful attempts of using simulation for the most-challenging in-flight tasks. These studies provided valuable data for improving the validity of other studies conducted on the VMS and elsewhere.

UH-60A Simulation Validation (1984-1993)

Several organizations cooperatively conducted the first attempt to compare how well the VMS could simulate helicopter flight (Ref. 8). Pilot handling qualities ratings (HQRs) were Level 1 (satisfactory without improvement) in flight but Level 2 (not satisfactory without improvement) 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. 9. This experiment compared performance and pilot opinion using a UH-60 flown at 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. Improvements were self-evident since the 1984 simulation, as the HQRs overlapped between simulation and flight, but the pilots noted deficiencies in the visual and heave motion cueing. Field-of-view in the simulator was inadequate for some tasks, and the lack of texture and detail in the simulated visual scene made the simulated tasks more difficult than the in-flight tasks. The heave motion cue in simulation was noted to be marginal, and it made the anticipation of finding the proper stopping point during the bob-up (an altitude repositioning task) difficult.

Initial Cueing Fidelity Studies (1985-1999)

Early research by Bray (Ref. 10) on the VMS showed how far removed the simulated cues in a typical helicopter are from the real world and exposed the need for systematic investigations with objective measures to determine fidelity requirements. Bray observed that while pilot-vehicle performance and opinion is sensitive to degradations in motion and visual cues, pilot opinion has not been particularly helpful in identifying the *source* of these deficiencies. Thus, objective measures of fidelity were required.

Early studies emphasized the relative timing between the visual and motion cues that was a suspected cause of simulator sickness. This was a concern with all training simulators and a particular concern in the VMS. Given the salient nature of the increased motion cues in the VMS, it was a natural facility to investigate simulator sickness. Using four different motion conditions, McCauley (Ref. 11) found that simulator sickness increased with both time and the level of maneuvering. Using a UH-60 model, Sharkey (Ref. 12) subsequently found that false motion cues had an adverse effect similar to having no motion cues.

The effects of asynchrony between the motion and visual cues were also investigated for handling qualities effects. Mitchell and Hart (Ref. 3) 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. 13) studied the motion and visual synchrony among the roll and lateral axes using a predominantly lateral axis task. They 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. This went against the prevailing conventional wisdom that believed the motion cue should not lag the visual cue.

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. The only instance when this trade-off maybe avoided is when the task requires displacements that are within the physical envelope of the simulator used. The Ref. 13 study considered such an instance for a sidestep task in the VMS for which 1:1 motion was possible. It is reasonable to conclude that such studies add to the validity of motion-and-visual fidelity investigations, as the motion system is providing the full physical motion as calculated by the mathematical model.

Considering the effects of motion cues on handling qualities, Mitchell (Ref. 14) 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. A reason for this preference is that, if the immediate acceleration feedback cue provided by the motion gain is more representative of the acceleration the model is actually producing, it allows the pilot to adjust his input to achieve the desired level of aggressiveness.

Schroeder (Ref. 15) 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. Tracking errors increased significantly when all motion was removed. 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. 16) evaluated the proposed Sinacori motion fidelity criteria. 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).

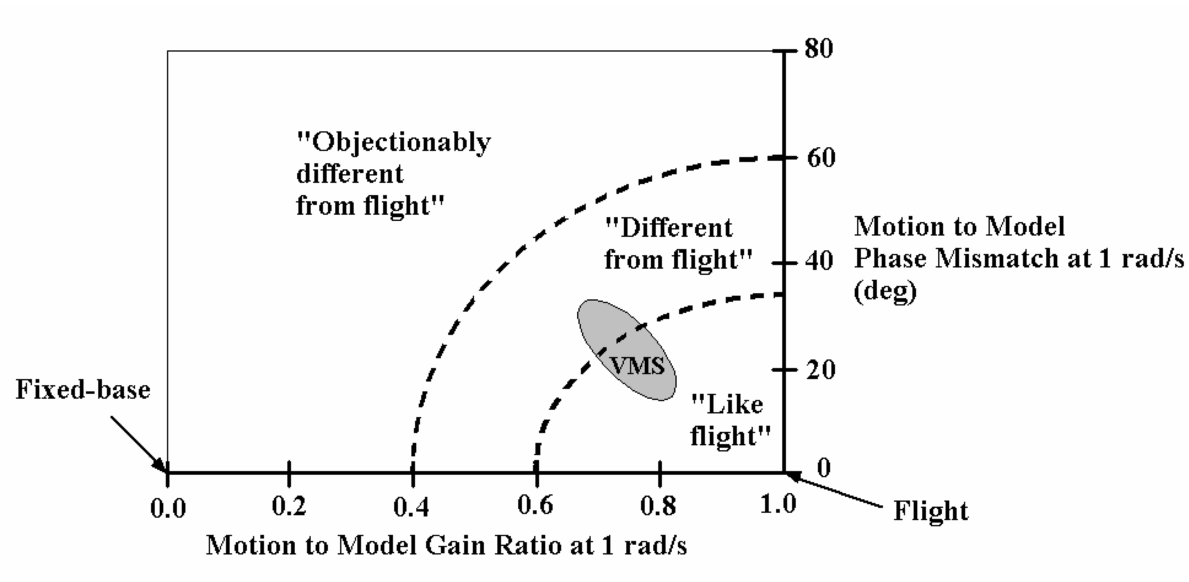

Figure 5. Motion Fidelity Criteria

A question that often arises when configuring the motion system is the level of fidelity required in each axis. That is, should the reduction in cue be equivalent in all axes or should it be weighted in favor of one axis over the other? It appears that all of the motion cues are not of equal importance when combined with other motion cues, visual cues, or both. The earlier study that showed little effect of yaw cueing led to a more detailed study (Ref. 17), which 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 combined with compelling visual yaw rotational cues, then the yaw motion system rotational cues might be redundant and unnecessary.

In a study that considered visual cueing aspects as well as motion, Johnson (Ref. 18) investigated variations in how the displayed level-of-detail might change in the image generator as one gets closer or further away from an object for a height control task. Platform motion was also a variable. The results showed that changing the level-of-detail to maintain constant optical density as the altitude changed, like that of the real world (yet different than how visual systems provide it), improved altitude awareness. 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. 19). 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. 20). 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.

Cueing Requirements for Autorotation and Shipboard Landing (1982-2001)

The VMS was used to evaluate cueing effects on autorotation in two studies separated by more than a decade (Refs. 21 and 22). In the first study, autorotation task performance decreased with degraded motion cues, yet acceptable performance could be attained as long as adequate visual cues were present. In the second study with improved visual cueing technology, the effect of visual texture and motion variations on autorotation task performance were evaluated. Visual texture affected all measures, but the finest texture did not perform the best, debunking a myth that more texture is better, as one has to be mindful of the aliasing that can occur due to both the image generator and human visual dynamics. This result was also supported by a fixed-base psychophysics study (Ref. 23). Visual detail affected only pilot subjective opinion. Pilot performance, as well as opinion of motion fidelity, improved with increased motion cueing.

Two simulation studies were conducted under the Dynamic Interface Modeling and Simulation System as part of the Joint Shipboard Helicopter Integration Process (JSHIP), to investigate the simulation fidelity required to recreate the shipboard-landing task accurately (Ref. 24). Considerable effort was placed on achieving the visual and dynamic fidelity required to ensure that pilot workload was consistent with that experienced in the actual task. This study was preceded almost two decades earlier by a similar one that evaluated whether high-fidelity simulation could be used for assessing the shipboard landing environment using the VMS and a model of a SH-2F helicopter (Ref. 25). The more recent simulation showed that the significant improvement in vehicle modeling and visual display fidelity in the time period between these studies had made the overall cueing environment more realistic, but that challenges remained in accurately modeling and simulating the ship airwake and its interaction with the rotorcraft.

Adverse pilot-vehicle interactions:

A study by Schroeder in 1997 (Ref. 26) evaluated the effect of simulator platform motion on predicting Pilot Induced Oscillations (PIOs). The goal of the study was to understand the level of motion fidelity necessary to reproduce PIOs observed in a previous in-flight experiment (Ref. 27). Three platform motion characteristics were examined: large, small, and no motion, where small motion simulated the motion envelope of a conventional hexapod with 60-in stroke actuators, and large motion used the full range of motion available on the VMS. Pilot opinion ratings and performance data from the study indicated that large motion was necessary to match the results of the in-flight experiment. The results indicated that the pitch-rate cues from small and large motion were both adequate, but the more realistic vertical acceleration cues available in the large motion made the difference in pilot performance and opinion.

A study by Hoh in 2006 investigated rudder flight control system requirements for passenger aircraft (Ref. 28). Specifically, the study investigated the rudder control system characteristics that could contribute to pilot overcontrol or PIO in the directional axis. A primary objective of the study was to assess the role of motion cueing fidelity on pilot perception and tendency to PIO. To this end, experimental configurations were evaluated using the full motion envelope of the VMS and a simulated hexapod motion envelope using a directional control task. Here again, pilot opinion data and comments indicated that full motion provided more compelling and accurate cues for this task than the simulated hexapod.

These studies indicate that a range of motion similar to that available on the VMS is required for providing the level of realism necessary to ensure that pilot cueing modalities and control technique does not differ significantly from flight for the evaluated tasks. They serve as a point of departure for further research on the minimum motion fidelity required for various flight tasks.

VSTOL Aircraft Research

VSTOL aircraft research from two broad programs by NASA and other collaborating agencies accounts for approximately 60% of the simulations conducted at the VMS. The two programs developed technologies for rotorcraft and short take-off vertical landing (STOVL) aircraft that are presently incorporated in modern rotorcraft and the F-35B Joint Strike Fighter (JSF), respectively. The rotorcraft research began in earnest in the 1970s as the US Army recognized that understanding of rotorcraft performance and flying qualities issues had to be expanded and improved to provide a solid base of knowledge for designing and developing the next generation of military rotorcraft. This eventually led to the development of a military standard for rotorcraft handling qualities, and modern flight control and pilot-vehicle interface technologies. A similar recognition of the deficits in understanding jet-lift aircraft and the need to develop new flight control concepts for these aircraft resulted in another multi-agency program that led to the flight control technologies incorporated in the JSF. In both cases, data and insights from VMS simulations reduced technical risk and enhanced safety by maturing concepts and technologies in a safe but realistic environment.

STOVL Aircraft:

The flight control requirements for STOVL operations were examined using simulations on the VMS and flight tests under the NASA/UK MoD Joint Aeronautical Program between 1980 and 1996. In parallel, the advanced short take off and vertical landing program initiated by the Defense Advanced Research Projects Agency investigated flying qualities requirements for integrated flight and propulsion concepts. The JSF program and the manufacturers leveraged this body of knowledge to design the X-32B and X-35B prototypes leading to the selection of the F-35B as the next generation of fighter/attack aircraft for the US and UK (Ref. 29).

Research in support of these programs included flying qualities for advanced control modes, maximum control power used, control system dynamic response associated with thrust transfer rates for attitude control, thrust margin in the presence of ground effect and hot gas ingestion, dynamic thrust response for the engine core, and flight path control during transition (Ref. 30). Determining flight control and aircraft performance requirements for shipboard landing were the focus of many of these studies and the high-fidelity motion cueing available on the VMS provided confidence that the simulation results would translate to flight. In one study to evaluate minimum thrust-to-weight ratio required for precise vertical control prior to shipboard landing, the VMS was configured to provide 1:1 motion in the vertical axis to provide the most realistic vertical motion cueing to the pilots. The study established the thrust-to-weight ratio required for satisfactory performance in controlling sink rate during shipboard landings (Ref. 29).

Rotorcraft Handling Qualities:

In the 1970s, the Army needed a handling qualities specification that could guide the development of rotorcraft to 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. 31). 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 remedy this, the U. S. Army Aeroflightdynamics Directorate (AFDD), in collaboration with NASA Ames, began an effort to build a database of handling qualities data and design criteria that could be incorporated into a new handling qualities specification. The VMS was central to this effort from the outset. In 1982, the AFDD began the development of a new rotorcraft handling qualities specification to supersede MIL-H-8501A (Ref. 31). The specification, US Army Aeronautical Design Standard – 33 or ADS-33 (Ref. 32), was completed and published in 1987. Initial development of the specification was for the procurement of the modern light/attack/scout helicopter by the Army leading to the development of a prototype helicopter, the RAH-66 Comanche. Sikorsky Aircraft built and flew two prototypes; however, the Army cancelled the production program in 2004 to provide renovation funds for its existing helicopter fleet.

The strategy for developing a helicopter handling qualities database of sufficient 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, and simulation studies on the VMS continue to fill known gaps in the database and refine others.

Early studies investigated the effect of design variations on rotorcraft dynamic characteristics and handling qualities. Later studies investigated some of the fundamental precepts under development for the specification – required response type and response bandwidth (Ref. 32). An innovative concept introduced in ADS-33 is the trade-off between augmentation (which defines response type) and the visual cueing environment. 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 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.

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 on the CH-47F which was evaluated on the VMS (Ref. 33). The RAH-66 control system design was, in turn, based on extensive research on the Army's advanced digital optical control system program that also used the VMS for initial design and development.

Spacecraft Research:

Spacecraft research on the VMS began soon after it was built, with engineering development studies of the Space Shuttle Orbiter. Simulations on the VMS made important contributions, starting with initial engineering studies in 1979 and 1980 to refine the Orbiter flight control system prior to first flight (Ref. 34). Subsequently, NASA used the VMS for engineering studies on longitudinal and lateral handling qualities evaluations, and landing rollout systems and procedures development. Over 20 Space Shuttle flight rules changes (changes in mission operation procedures) have resulted from engineering development studies conducted on the VMS (Ref. 35). Initial experience and success of the VMS as an engineering development simulator led to its use as an astronaut training simulator for the landing and rollout phase of flight.

Astronaut training sessions in the VMS are held semi-annually with each session containing unique objectives related to specific mission profiles and maintaining pilot training currency under nominal and off-nominal conditions. A Space Shuttle Mission Simulator team lead stated that the realistic pilot cueing environment in the VMS "by far affords the most realistic shuttle rollout simulation" (Ref. 36). Every Shuttle pilot has trained on the VMS and over 65,000 landing and rollout training and engineering runs have been completed.

As the US considers Shuttle replacement, studies on the VMS are evaluating the handling qualities and flight control system requirements for the next generation of US spacecraft – the Orion Crew Exploration Vehicle (CEV) and the Altair Lunar Lander vehicle. The ability of pilots to successfully carry out their missions will be determined in part by the handling qualities of these new spacecraft. Some operational tasks may be fully automated, while others will be manually controlled. Even for the nominally automated tasks, NASA requires a backup manual control capability when an automated system or critical sub-component of the spacecraft fails. In these cases of emergency reversion to manual control, when the pilot switches abruptly from monitoring to active control, it is even more important that the vehicle have good handling qualities. At this time, no reference standards exist for handling qualities of piloted spacecraft. Handling qualities data do exist for some space vehicles; however, the focus of these studies was on evaluating or addressing deficiencies in the handling qualities of an existing design for a specific vehicle. A more systematic approach is needed to map out handling qualities variations for a range of design variables and identify regions of satisfactory handling qualities in the design space for a class of vehicles.

A project to develop design guidelines for spacecraft handling qualities was initiated by NASA in 2007 and four simulations were conducted on the VMS with more to follow. Two simulations investigated the effect of flight control system and guidance display design on CEV handling qualities during docking with a simulated International Space Station (Ref. 37). Two simulations investigated the effect of control power and guidance display design on the handling qualities of the Lunar Lander during precision approach and landing (Ref. 38). With its realistic cues and flexible simulation architecture, the VMS could play a similar role in the engineering development and training with these new space vehicles as it did with the Space Shuttle.

Concluding Remarks

The NASA Ames Vertical Motion Simulator's motion system design leverages past experience with flight simulation at NASA Ames to achieve the best compromise between size and cueing fidelity necessary for flight research. The result is a ground-based flight simulator with an unmatched level of realism in pilot feedback cueing. This realism increases the likelihood that information and conclusions gathered from simulations on the VMS will translate to flight with few changes, thus enabling the VMS to be the best available ground-based alternative to flight testing. This realism has, over the past three decades, enabled researchers using the VMS to generate a wealth of data and knowledge that has enhanced the understanding of pilot cueing and the art of simulating these cues with minimum loss of fidelity. It has also provided critical design data on aircraft handling qualities and for flight control development resulting in reduced risk for major programs such as current rotorcraft flight control system upgrades and the Joint Strike Fighter.

The high fidelity cueing environment also enabled the VMS to play an important role in the Space Shuttle program as an engineering development tool and later as a pilot training tool. Its ability to recreate pilot cueing in unconventional vehicles is presently exemplified by its use in evaluating the handling qualities and flight control requirements for the next generation of US spacecraft. Engineered for realism, the VMS is a safe and cost-effective solution for research and development of vehicles and human-vehicle interaction concepts.

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