THE MOTION GENERATOR FOR THE ROTORCRAFT SYSTEMS INTEGRATION SIMULATOR

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ABSTRACT

Since World War II, the U.S. Army has considerably expanded its use of the helicopter in a variety of military functions. As new missions were defined, new tactics, extended performance requirements and increased number of subsystems have imposed extreme demands on the pilot. Ground-based flight simulation is the only safe practical way to investigate the tradeoffs between a better-trained pilot and a more complex aircraft. In 1975, a joint U.S. Army and NASA study was performed to establish the future needs for the simulation of rotary-wing aircraft. As a result, a program was initiated to develop a facility that could be used by government and industry in research and development. That facility is being developed jointly by the U.S. Army and NASA at the Ames Research Center.

In 1978 the Franklin Research Center completed the development of the concept for the motion generator to satisfy the requirements of the new simulation facility. In 1979 they began the design of the unit which is to be installed at the Ames Research Center in 1982. The Rotorcraft Simulator Motion Generator (RSMG) is a new four-degree-of-freedom system to replace the synergistic motion system presently mounted on the Vertical Motion Simulator at Ames. Its extended capabilities will satisfy the requirements for research involving both fixed-wing and rotary-wing aircraft. In this way the Army/NASA goals for an advanced facility for rotorcraft simulation are to be satisfied most efficiently.

INTRODUCTION

Although the U.S. Army accepted delivery of its first helicopter 40 years ago, it was not until after the Korean War that the necessary doctrine and experience were available with which the development of a military helicopter could begin in earnest. The greatest impulse to progress in helicopter development resulted from the requirements and experiences in the Korean, Viet Nam and Middle East wars.

In the three decades since the end of World War II, the U.S. Army has considerably expanded its use of the helicopter. Originally, the helicopter was thought of as being a reconnaissance, evacuation and general-purpose aircraft that was capable of performing missions similar to those that had been performed by the light, fixed-wing aircraft. As the potential of this vehicle began to be appreciated, its use added another dimension to the battlefield by enhancing the Army's ability to conduct the land combat functions of mobility, intelligence, firepower, combat service support, and command, control and communication. Helicopters are now recognized by the U.S. Army as important replacements for traditional ground vehicles in the performance of certain missions that are beyond the capability of fixed-wing aircraft. As the helicopter has acquired these new missions, it has also acquired new tactics, new performance requirements, and a tremendous increase in the number of subsystems, most of which require some degree of management or control by the pilot.

Training alone may no longer enable the pilot to cope with the situation. It is possible that regardless of the extent of training, we are approaching the limit of the human pilot's capability. Of course, the helicopter could be made easy to fly or even to fly itself in these new missions, but such benefits are costly. Automation can significantly increase cost and complexity, and adversely affect reliability and maintainability. To be cost effective, the military helicopter must make full use of its pilot and his capabilities. However, he must not be overloaded to the extent that his mission performance is degraded or his margins for error are decreased until there is an increased susceptibility to accidents. Ground-based flight simulation is the only safe and practical way to investigate the trade-offs systematically before hardware is developed.

Over the last 20 years or so, ground-based flight simulation has become a recognized and widely accepted training tool. In the fixed-wing aircraft industry, the cost effectiveness of ground-based flight simulation in research and development has also been demonstrated (1). Flight simulators have been used to a far lesser extent by the rotary-wing industry. In 1975, a joint U.S. Army and NASA study was performed to review the functions, status and future needs for ground-based flight simulation of rotary-wing aircraft. In the course of this review, the deficiencies in current simulation capability relative to rotary-wing aircraft requirements were identified. As a result of that review (2), a program was initiated to develop a high-fidelity rotorcraft simulation capability that could be exploited by both government and industry in research and development. The simulation capability is being developed jointly by the U.S. Army and NASA at Ames Research Center.

USES OF A ROTORCRAFT SIMULATOR IN RESEARCH AND DEVELOPMENT

The 1975 Army/NASA study concluded that the needs for a helicopter R&D simulator fell into the following two categories:

1. In support of basic technology. This work consists of generic studies of stability

and control, handling qualities, controls and displays, and other aspects of the man-machine interface.

2. In support of the development of new aviation systems or improvements to fielded systems. These efforts start early in an aircraft acquisition cycle by assisting the user and the developer in performing design studies, system integration evaluations and trade-offs.

The first of these uses permits us to address the fact that current helicopter flying qualities specifications are based on an obsolete design standard. For our newest helicopters, we have had to devise poorly substantiated criteria for new missions and tasks. Therefore, in our current R&D program we are pursuing the development of a technological data base in rotorcraft handling qualities that should enable us, for the first time, to generate the criteria and the specifications on flying qualities for rotary-wing aircraft designed to perform military missions (Figure 1). Ultimately, the intent is to provide the designer with the matrix of information he needs to relate effectiveness to life-cycle costs.

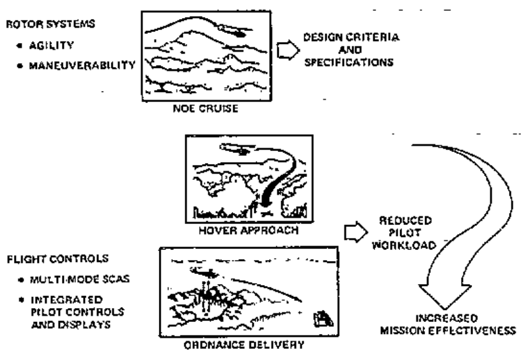

Figure 1. Helicopter Handling Qualities Research

The development of a handling-qualities specification for use by helicopter manufacturers in the design phases would benefit both the industry and the government. Experience has shown that the use of the current handling-qualities specification (MIL-H-8501A) has failed to provide more than basic guidance to industry and attempts to meet the requirements of that specification have, in many instances, resulted in undesirable flying qualities (3). Individual specifications were developed for the Utility Tactical Transport Aircraft System (UTTAS) and the Advanced Attack Helicopter (AAH) in an effort to eliminate this deficiency; but both helicopters, although judged to have superior flying qualities, also failed to meet certain requirements of their specifications (4). From an aeromechanics point of view, our most modern U.S. Army aircraft, the UTTAS and the AAH, are based on technology that is 10 to 20 years old. These aircraft, like their predecessors, will impose workloads on their aircrews during typical Army missions that will constrain the pilot from exploiting to the maximum the full capabilities of his aircraft, especially at night or under adverse weather conditions.

Rotor systems and their associated controls offer the most direct method of improving flying qualities and reducing pilot workload in the missions and tasks typically assigned to Army helicopters. Chen and Talbot (5) investigated four major rotor system design parameters to assess the handling qualities for 44 configurations of main-rotor systems that cover teetering, articulated, and hingeless families of rotor systems with a wide range of blade inertia. They concluded that within each family of rotor systems, satisfactory handling qualities could be obtained with the appropriate combination of rotor parameters. However, no single rotor system was uniformly superior in all aspects of handling qualities during typical operations. Additional experiments such as these are required to optimize the handling qualities for specific missions.

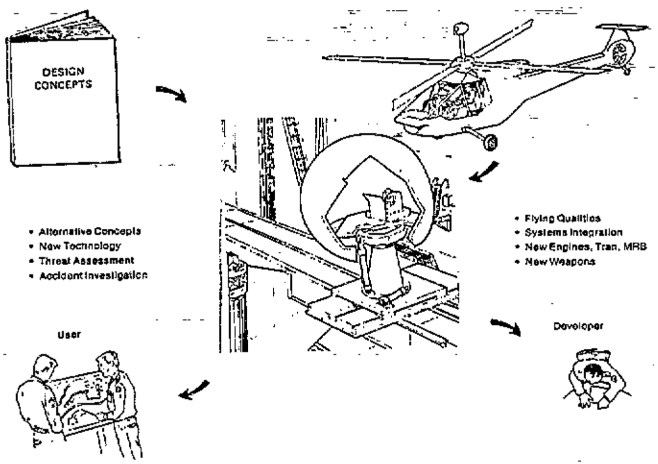

Figure 2. Systems Development Cycle

The second use of R&D flight simulators, during the development of new aviation systems for improvements to fielded systems, follows the entire life cycle of system development (Figure 2). During the program initiation phase, the simulator can be used to evaluate new aviation concepts or tactics that have been developed by the U.S. Army Training and Doctrine Command (TRADOC) to meet a specific threat. The R&D simulator also provides an ideal environment for evaluating the threat from both ground weapons and enemy helicopters. The probability of air-to-air combat between helicopters on the future battlefield is extremely high. Success in these engagements may depend on exploitation of weakness in the threat helicopter's handling qualities or in the optimization of our own flight maneuvers. It may be in this approach to establishing requirements that ground-based simulators will play their most effective role in minimizing the life-cycle cost of our future aircraft. Such evaluations can help answer the questions and support the rationale leading to a Mission Element Needs Statement (MENS). After the MENS is approved, the R&D simulator can be used in the demonstration and validation phase for evaluating the flying qualities of competing designs as well as for easing future systems integration efforts.

Manned simulation also plays an important role in establishing hardware configuration during the development of the helicopter. During the evaluation phase of a baseline design, test pilots and operational pilots are provided the opportunity, through manned simulation, to evaluate the baseline and mission scenarios with full operational freedom. This is the last point in time when changes to the baseline design can be made without extremely costly hardware retrofit. Also, actual prototype flight hardware can be incorporated into the flight simulator. Although standard bench integration test will verify electrical and, in some cases, software compatibility, only a dynamic simulation can completely exercise the equipment. Even more important, all aspects of the software can be tested in a mission enviroment well before the aircraft flies.

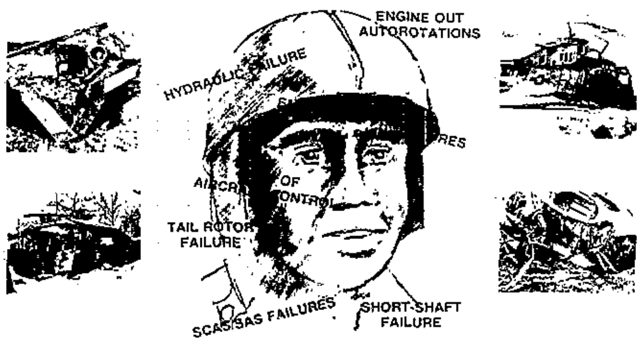

Figure 3. Aircraft Accident Investigation

Finally, the R&D simulator can be used to investigate unusual accidents (Figure 3), the understanding of which defines normal investigative techniques. One such investigation has already been accomplished at Ames Research Center. In March 1976, a Bell Helicopter Textron Model 214 helicopter crashed during hardover-control-signal testing of its Automatic Flight Control System (AFCS). The subsequent accident investigation did not conclusively establish the cause of the accident but did indicate that it was not caused by a mechanical, electrical, or hydraulic failure. It was decided to continue the investigation using the six-degree-of-freedom Flight Simulator for Advanced Aircraft (FSAA) at Ames Research Center. The results proved that removing the hardover-control-signal at the same time the pilot was taking corrective action causes large spikes in blade flapping and was the probable cause of the accident. The procedure for hardover-control-signal testing was subsequently modified and similar accidents have not occurred.

In summary, flight simulation is an important tool in helicopter research and development, both for technology-base development and for aircraft development programs. There is no question that ground-based simulation has been and will continue to be an invaluable tool. The flight simulator is to the flight dynamicist what the wind tunnel is to the aerodynamicist. The emphasis on the control of development costs and operational training costs suggests that flight simulators will play an increasingly important role in future research and development of Army rotary-wing aircraft.

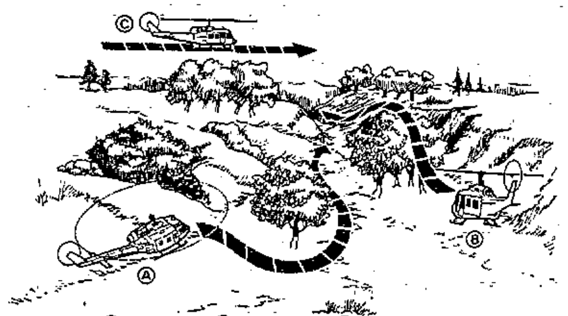

Figure 4. Terrain Flying Regimes

REQUIREMENTS OF A RESEARCH AND DEVELOPMENT ROTORCRAFT SIMULATOR

The modern battlefield has become a highly lethal place for both fixed- and rotary-wing aircraft. The formidable array of weapons that can be used against aircraft has forced pilots to abandon their normal operating altitudes in the vicinity of a battlefield. The only air space that can be considered relatively safe is below 100 feet and then only if a sufficient amount of ground cover is available. The helicopter is naturally a ground contact machine par excellence and its mission use in Army aviation is more characteristic of a flying jeep or tank than of an airplane. Helicopters fly low and slow and, especially during military missions, are close to the ground during most of their flying time. The term nap-of-the-earth (NOE) (Figure 4) has been coined by the helicopter community to describe operations in which helicopters fly only a few feet above the ground and fly around obstacles rather than over them. The environment for the pilots flying these missions is rich in detail--trees, bushes, hills and valleys. Although these terrain features offer protection from the enemy, they can be lethal to an unwary pilot. In addition, visibility factors associated with weather and darkness, and atmospheric characteristics of wind, turbulence and ground effect are all elements of the environment that may significantly affect the helicopter pilot's tasks. The helicopter crew must maneuver around and between obstacles, and navigate, communicate and proceed with the mission while maintaining awareness of threat weapons.

Current simulation capabilities cannot meet the requirements of rotary-wing aircraft when one considers all the aspects, including mission, task, aircraft characteristics, environmental conditions, instrumentation and displays, performance and workload. Many of these aspects impose requirements quite different from those met by even the most sophisticated fixed-wing simulators. The most advanced ground-based simulators in the world are available to the U.S. Army's Aeromechanics Laboratory (through agreements with Ames Research Center), but even these are not adequate to meet the Army's need to simulate nap-of-the-earth flight operations. The visual display is required to represent much more detail in the terrain and vegetation. Low flight speeds and high maneuverability allow rapid changes of flightpath to be achieved so that the field of view required for the helicopter pilot to see where he is going is wider than that of a fixed-wing aircraft. This paper, however, concerns itself with the requirement for motion. Deel and Rue discussed visual concepts (6) during the last conference.

Motion (Platform) Requirements

There is no obvious and accepted measure of motion cue requirements. It is generally agreed that motion simulation is required: (1) when expected motions are above human sensory or indifference thresholds; (2) when expected motions are within the sensory frequency range, that is, above 0.2-0.5 rad/sec; (3) if full pilot performance (e.g. tracking) is desired; and (4) when a degree of face validity or realism is required to gain pilot acceptance of the total simulation.

An example of relating simulator motion system capabilities to the maneuver envelope of an aircraft is presented in a paper by Key et al (7), which includes a description of the development of the requirements for a motion system to be used in a helicopter flight simulator.

Axis	Parameter		
	Position, rad, m	Velocity, rad/sec, m/sec	Acceleration, rad/sec^2, m/sec^2
Yaw	$\pm$0.4	$\pm$0.6	$\pm$1.0
Pitch	$\pm$0.3	$\pm$0.5	$\pm$1.0
Roll	$\pm$0.3	$\pm$0.5	$\pm$1.0
Surge	$\pm$1.3	$\pm$1.3	$\pm$3.0
Sway	$\pm$3.0	$\pm$2.6	$\pm$3.0
Heave	+7, -14	+6, -11	+14, -12

Table 1. Motion (Platform) Requirements for Critical Terrain Flight Maneuvers (from Reference 7)

The criteria that were adopted for these requirements were based on the opinions of experienced researchers, which in turn were supported by limited test data. Flight maneuvers resulting from fixed-base simulations of NOE flight operations were analyzed to define the platform excursion requirements. These time histories were played (off-line) through a drive logic representing that of an advanced six-degree-of-freedom simulator, with the fidelity boundaries and selected operating points for each axis. The results of the analysis, in terms of the maximum excursion, velocity, and acceleration of each axis, are presented in Table 1. The requirement is that all axes produce these quantities simultaneously; this requirement is amplified by the data of Table 2, where the position of each axis at the instant that one axis reached a maximum is presented. The data are from a typical maneuver case. The significance of the data is then when one axis is at a maximum, some of the others are at large values also. A nonlinear drive logic is needed to vary the gains and washout frequencies with amplitude of motion in order to obtain as much fidelity as possible for lower amplitude tasks.

Axis at maximum position	Simultaneous axis position, % maximum					
	ϕ Roll	Θ Pitch	ψ Yaw	X Surge	Y Sway	Z Heave
ϕ	100	0	31	0	92	73
Θ	60	100	6	83	46	14
ψ	67	22	100	28	54	41
X	33	33	-19	100	0	59
Y	87	33	38	83	100	-77
Z	47	33	0	56	69	100

Table 2. Examples of Simultaneous Excursions (from Reference 7)

RSIS PROJECT PLAN

Under joint agreement, Ames Research Center and the U.S. Army Research and Technology Laboratories, Aviation Research and Development Command (AVRADCOM), have agreed to acquire the Rotorcraft Systems Integration Simulator (RSIS) to be installed at Ames Research Center. The program is now in its final phase. The definition phase started with an Army/NASA study in 1975 which led to additional studies to address the issues raised by the special requirements of rotorcraft simulation. A feasibility study of a wide-angle visual simulation system, completed by Northrop in 1977, showed that a wide field-of-view display (120° horizontally by 60° vertically) was feasible. Analyses of fixed-base and motion-base simulations of NOE flight operations have defined the cab excursions required for high-fidelity simulation motion. It was determined that the Vertical Motion Simulator (VMS) at Ames Research Center could be modified and used as the motion base of the RSIS (Figure 5). Independent design studies to assess the possible modification to the VMS were performed by Franklin Research Center and Northrop Corporation in 1978. Specifications were developed from those two studies, a competitive request for proposal was issued to industry and the contract was awarded to Franklin Research Center in 1979. The modification, known as the Rotorcraft Simulator Motion Generator (RSMG), will be delivered in late 1982. The remainder of this paper will discuss the design and the fabrication of the RSMG by the Franklin Research Center (FRC).

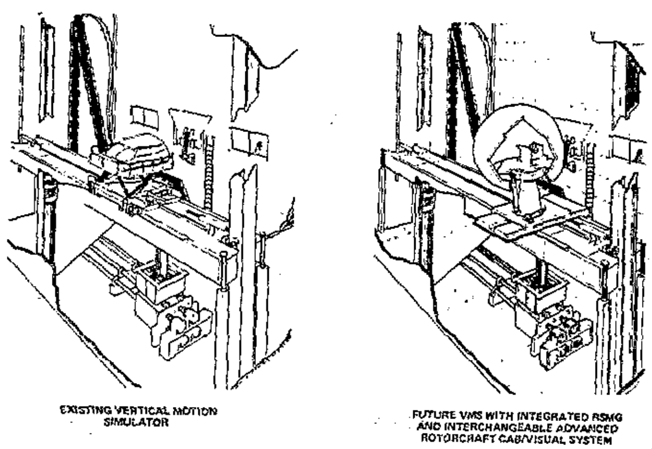

Figure 5. The Vertical Motion Simulator

DESIGN STUDIES FOR THE ROTORCRAFT SIMULATOR MOTION GENERATOR (RSMG)

Motion Generator Specification

As a result of the analyses performed by the U.S. Army Aeromechanics Laboratory and the National Aeronautics and Space Administration at the Ames Research Center, specifications were developed for the Rotorcraft Simulator Motion Generator (RSMG) as shown in Table 3. The severe limitation on

1. Performance

Mode	Simultaneous Displacement	Velocities	Acceleration
Longitudinal (X)	± 1.22 m (± 4 ft.)	± 1.22 m/sec (± 4 ft./sec)	± 3.05 m/sec^2 (± 10 ft/sec^2)
Roll (Ø)	± 0.314 rad (± 18°)	± 0.7 rad/sec (± 40°/sec)	± 2.0 rad/sec^2 (± 115°/sec^2)
Pitch (θ)	± 0.314 rad (± 18°)	± 0.7 rad/sec (± 40°/sec)	± 2.0 rad/sec^2 (± 115°/sec^2)
Yaw (Ψ)	± 0.418 rad (± 24°)	± 0.8 rad/sec (± 46°/sec)	± 2.0 rad/sec^2 (± 115°/sec^2)

2. Payload
   - Configuration: 20.5 ft. dia. sphere section
   - Gross Weight: 8000 - 12,000 lbs.
   - Moments of Inertia: 3000 - 20,000 lbs. ft. sec.^{2}
3. Frequency Response
   - Second order system natural freq. 3 Hz and damping factor 0.7
   - Tolerances, ± 2 db and ± 20 degrees
4. Weight Limitation

   Total weight of 4DOF system < 16,000 lbs.

Table 3. Specifications for the Rotorcraft Simulator Motion Generator (RSMG)

the weight of the RSMG was imposed so the performance of the Vertical Motion Simulator (VMS) would not be degraded from its original performance goals. In addition there were severe constraints on the operating envelope of the RSMG due to the internal dimensions of the existing VMS building structure. Most critical, of course, is in the direction of longitudinal motion where the 20 foot diameter sphere must be allowed a total displacement of 8 feet within a building dimension of 31 feet.

Studies of RSMG Candidates

A number of RSMG configurations were analyzed in an effort to meet all requirements in the most cost-effective manner (8). Brief descriptions follow.

Since the synergistic type of motion system, illustrated in Figure 6, is the most efficient machine for generating six-degrees-of-freedom (6DOF) motions it was considered first. Design calculations showed that the actuator lengths required to provide all displacements simultaneously were unreasonably long (30 feet). In addition, a failure mode analysis showed that under certain emergency conditions, the platform could assume an attitude that would cause the 20 foot sphere to strike the building wall.

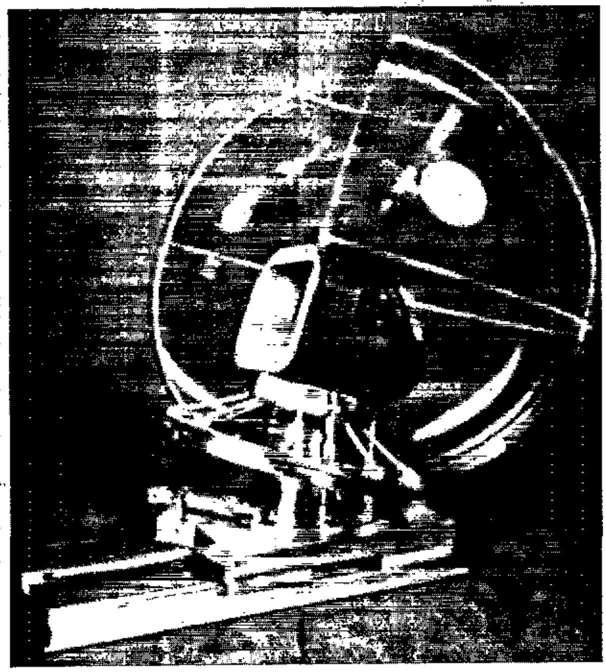

Figure 6. Synergistic 6DOF Motion System

The opposite extreme is a cascaded system as shown in Figure 7 where the sphere is carried on three rotational gimbals which are, in turn, mounted on a longitudinal carriage. This configuration captures the sphere within the range of the longitudinal motion under all operating or emergency conditions. However, the weight of the

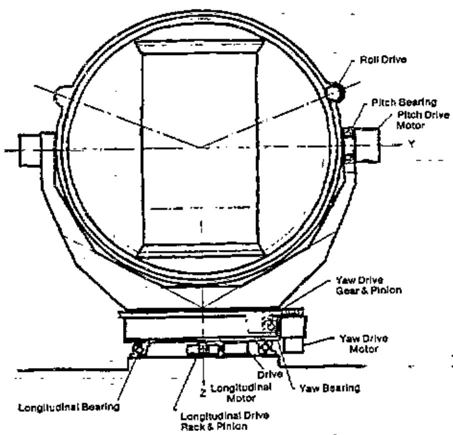

Figure 7. Cascaded 4DOF Motion System

cascaded gimbals and carriage structure not only severely escalated the power requirements of the drive system, but also far exceeded the allowable limit imposed on the total RSMG weight.

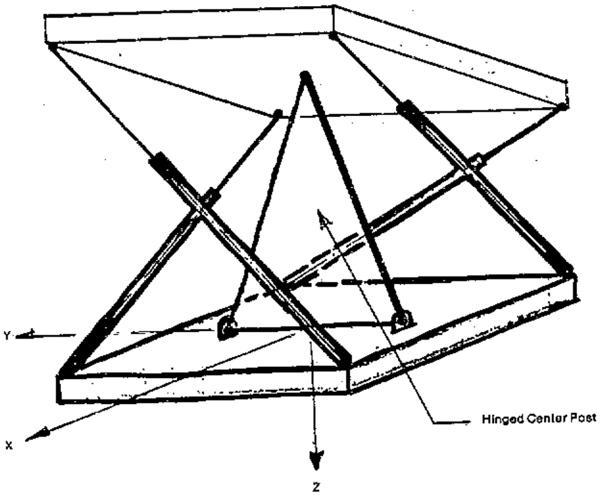

Figure 8. Synergistic 4DOF Motion System

A synergistic 4DOF configuration, shown in Figure 8, was investigated next. It has a hinged center-post that eliminates lateral motion and limits vertical motion, both of which are available from the basic VMS. Because of the minimization of moving mass, it is the most efficient configuration for generating the remaining 4DOF motions. However, again the actuators required to produce the specified displacements simultaneously were unrealistically long (34 feet) so the concept was rejected.

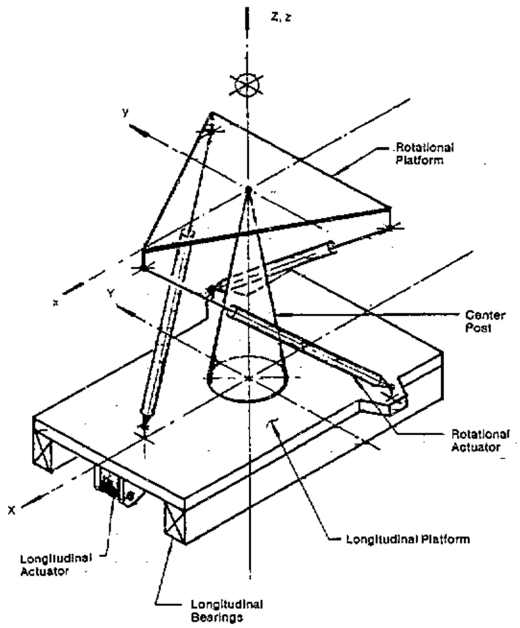

Figure 9. Synergistic 3DOF on Longitudinal Carriage

Recognizing the need to restrict actuator lengths, FRC elected to separate (or decouple) the translation motion from the rotational motions by using a carriage moving on linear ball bearings as shown in Figure 9. Here the rotational motions are produced with a synergistic arrangement of three actuators with a rigid center post restraining all translational displacements. A detailed design study of this 4DOF configuration revealed that all specified performance requirements for the RSMG could be met or exceeded. However, the overall height of the RSMG with the cockpit and dome in place required an unacceptable compromise in the available vertical displacement of the VMS.

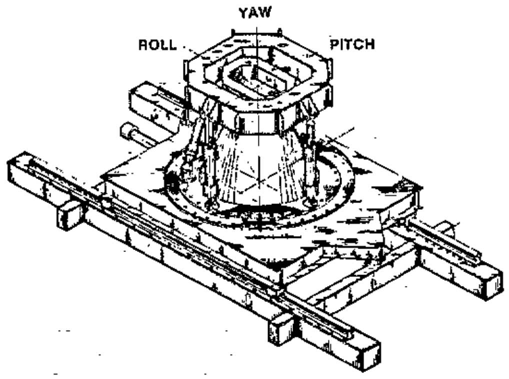

Figure 10. Final RSMG Configuration

The overall height was reduced by decoupling the yaw motion from pitch and roll as shown in Figure 10. Here the center-post is mounted on a large diameter ball-bearing carried on the longitudinal carriage. The platform is coupled to the center-post with a simple 2DOF universal joint restricting its motion to pitch and roll only. Since the actuators can now be positioned vertically and their length is relatively short, the overall height is reduced to meet the original goals for vertical motion of the VMS without impacting the ceiling of the building.

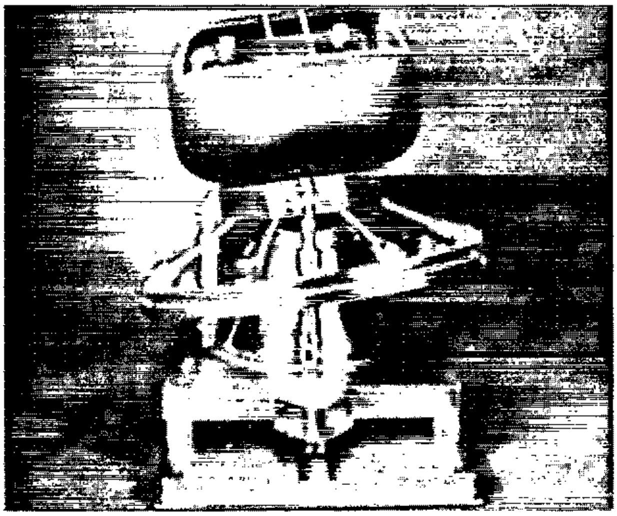

Figure 11. RSMG Model (without 20 ft. sphere)

The final configuration of the RSMG is shown in the model photos in Figures 11 (without the 20 foot sphere) and 12 (with).

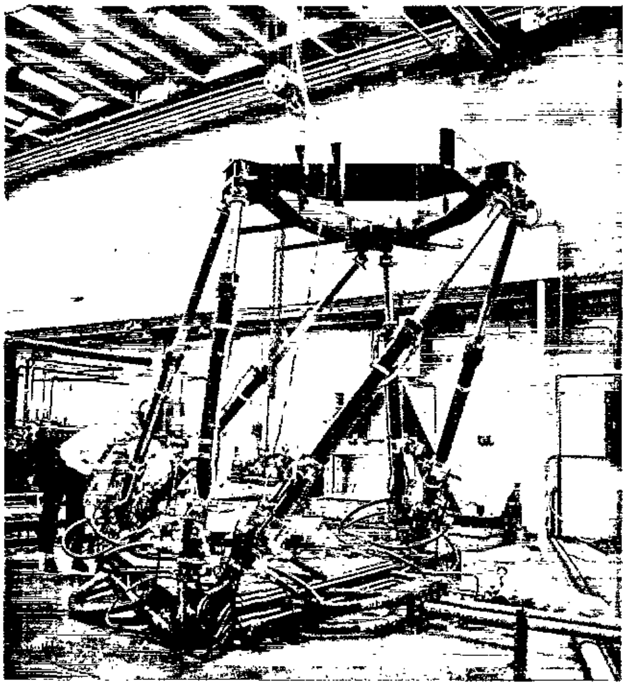

Figure 12. RSMG Model (with 20 ft. sphere)

ROTORCRAFT SIMULATOR MOTION GENERATOR (RSMG) DESIGN

Description of the RSMG System

The total RSMG system is made up of a number of subsytems as defined in the block diagram in Figure 13. The motion base is, of course, the central element to which all other elements are dedicated. It is driven with a set of four independent electrohydraulic actuators with feedback control loops and instrumentation for stabilizing and monitoring performance. The control systems are serviced by a hydraulic power supply and electric power. The control systems are commanded from a dedicated minicomputer which, among other things, provides the interface with the NASA host computer. The entire RSMG system is integrated with a set of built-in safety systems to protect men and machines in the event of any foreseeable emergency situation. The subsystems defined in Figure 13 are:

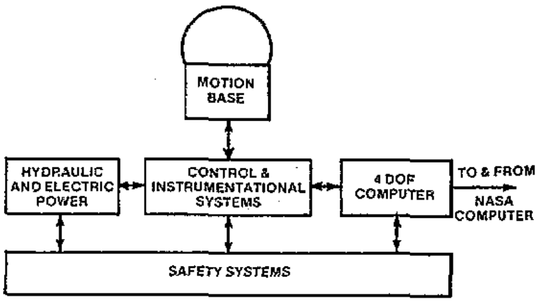

Figure 13. The RSMG System Complex

- Motion Base
- Controls and Instrumentation
- Hydraulic and Electric Power
- Dedicated Computer
- Safety Systems

Each of these subsystems will be described in greater detail in the sections that follow.

Motion Base

A sketch of the configuration of the motion base was shown in Figure 10 defining the four axes of displacements. The ± 4 feet of longitudinal motion is achieved with a carriage mounted on 32 linear recirculating-ball bearings on 2 linear tracks. Cross-sections of these bearings manufactured by THK Japan are shown in Figure 14. These bearings are precision-ground and pre-loaded to provide smooth noise-free operation without lost motion.

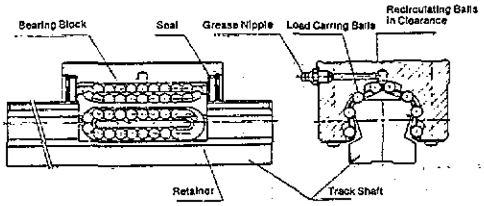

Figure 14. Cross-Sections of Linear Bearings.

The longitudinal carriage is driven with a single hydraulic cylinder centrally-located between the tracks under the longitudinal carriage. The design of all the cylinders on the RSMG is a patented telescoping configuration that provides equal effective hydraulic operating areas in both directions within the overall length of standard commercial unequal area cylinders. This provides for the symmetrical application of forces, minimizes the size of the servovalve required and optimizes the smoothness of motion.

The design of this unique equal-area cylinder configuration is shown in Figure 15.

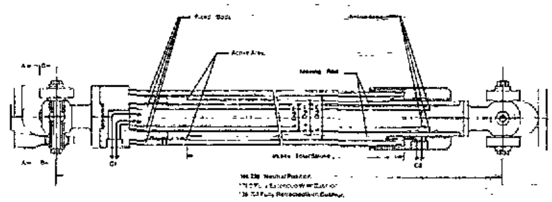

Figure 15. Typical Equal-Area Cylinder

The fixed portion on the left is made up of two concentric hollow tubes slightly shorter than the retracted length. The moving portion is a closed-end hollow tube with an annular flange that telescopes inside and between the fixed tubes. A seal is required around the moving tube and piston rings are required around its annular flange.

The left cylinder port allows the hydraulic fluid to enter the fixed center tube and impact the closed end of the moving tube. The right cylinder port conducts fluid into the annular area between the moving tube and the fixed outer tube to impact on the annular area projected by the flange. By proper selection of design dimensions it is clear that the effective area of the closed end of the moving tube can be made equal to or different from the effective area of the annular flange.

The $\pm 24^{\circ}$ of yaw displacement is provided by rotating a truncated-cone center post on a large diameter crossed-roller-bearing located in the center of the longitudinal carriage. It is approximately 48 inches in diameter and preloaded to avoid lost motion. It is driven by a single, equal-area hydraulic cylinder lying horizontal and attached between the longitudinal carriage and the outer radius of the center post.

Pitch and roll motions of $\pm 18^{\circ}$ are provided with a two-gimbal system mounted on top of the rotating center post. The equal-area drive cylinders are connected between their respective gimbals and the base of the rotating center post.

From the above description it is clear that, except for a minor geometrical interaction between pitch and roll displacements, the RSMG motion base is an "uncoupled" motion system. That is, individual motions are commanded independently, without the need for on-line coordinate conversion. This minimizes the requirements of the dedicated computer. It does not mean, however, that there is no coupling of the dynamics of the individual motions. Since the center of mass of the payload does not correspond with the center of rotation in the gimbal system, pitch accelerations will couple reaction forces into the longitudinal system and vice-versa.

<u>Controls and Instrumentation</u>

The first consideration in designing the electrohydraulic control systems is the servovalves. Over many years of experience, The Franklin Institute has developed a proprietary servovalve design that yields electrohydraulic controls that have a minimum of unwanted accelerations, commonly known as "hydraulic bump" or "acceleration noise". Current experimental tests under an Air Force contract indicate "smoothness" and/or "stability" better than 0.01g peak. The servovalves for the RSMG electrohydraulic controls are all of this special design. It involves an unconventional layout of the outlet ports of the third stage, which provides for more positive control of the outlet flow under the conditions of low actuator velocity.

To insure that the specified dynamic performance will be achieved in the operational system, each closed loop control system was carefully designed, mathematically modelled and simulated for computer analyses. The analyses performed on each of the four closed loop controls systems were:

- Frequency response
- Root locus plot
- Step response
- Force disturbance

Since the RSMG is a research simulator intended to be used with a variety of cab and visual display configurations, these analyses were performed with two extreme loads; one the cab and spherical screen described in the specifications, the other the NASA Interchangeable Cab (IC) with no external visuals. As an example of the results obtained, we will describe the design and analyses of the roll control system.

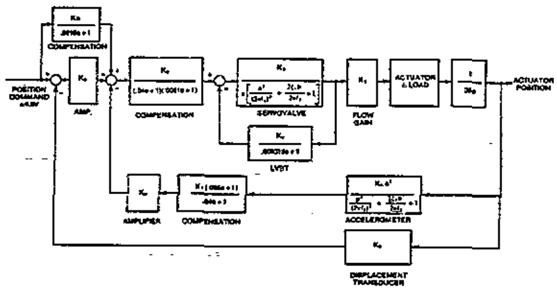

Figure 16. Block Diagram of Roll Control System

Figure 16 is a block diagram of the roll closed-loop control system. It uses a Trans-Tek angular position transducer as the primary feedback element. It also employs a Systron-Donner angular accelerometer to provide the compensation necessary to accommodate the wide range of expected loads. The position command is an analog signal from 0 to 10 volts dc. It is compared with the actual position feedback to generate an error signal which is compensated with acceleration feedback and shaping networks to command servovalve spool position. The servovalve has a Schaevitz LVDT spool position transducer in a minor loop to extend its bandwidth and responds accordingly to the error command to deliver flow to the roll actuator to reposition the load and minimize the error.

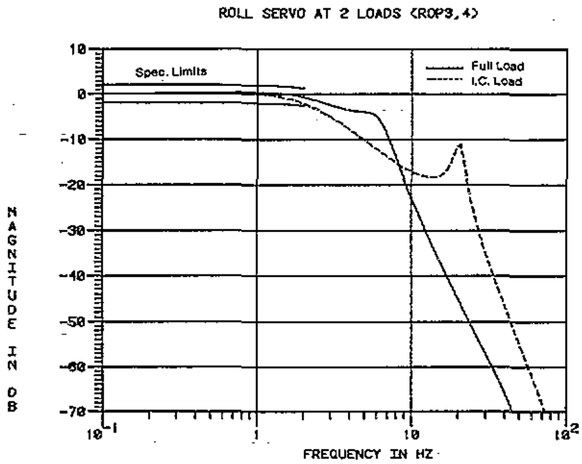

Figure 17. Frequency Response of Roll Actuator System

The frequency response of the roll actuator system is shown in Figure 17 together with the lines defining the limits set up in the specification. The analyses of the response to external force disturbances, such as coupling of reaction forces due to VMS lateral motion, indicate completely stable behavior.

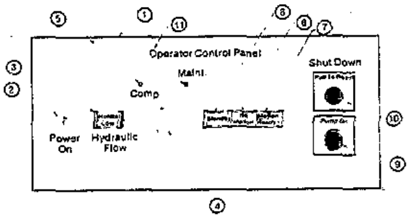

Figure 18. Operator's Control Panel

Control Consoles

There are two electronic consoles required to operate, monitor and maintain the performance of the RSMG system. One is a sloping-front console containing the Operator's control panel, the maintenance test panel, the control system electronics and all necessary DC power supplies. The Operator's panel is shown in Figure 18 indicating the simplicity of starting-up and controlling this complex machine under normal conditions. Figure 19 shows the maintenance test panel with the means to address each axis of motion separately and perform tests to insure proper performance. In the upper right corner is a computer-aided warning system that monitors critical system parameters, detects trends toward allowable limits and indicates the time to go until the RSMG is automatically shut down. This allows the Operator to use some judgment when he is in the middle of an important simulated test run.

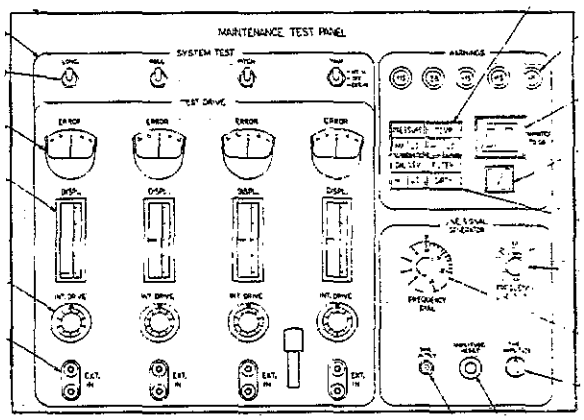

Figure 19. Maintenance Test Panel

The second electronic console is a tall relay rack containing a PDP 11/34 computer with disk unit, computer interface electronics, a system monitoring panel, a signal output panel and the safety interlock relays. It is to be located remotely from the vicinity of the Operator's console and addressed only during software changes and hardware troubleshooting.

Dedicated RSMG Computer

The central element of the RSMG computer system as a standard PDP 11/34 minicomputer with a CRT terminal and dual disk memories. To couple this computer with other subsystems three special circuit cards have been designed and built. These cards are:

- analog to digital (A/D) converter
- digital to analog (D/A) converter
- interface circuits

The A.D card is a 32 channel, 14 bit converter with analog multiplexers and instrumentation amplifiers. It accepts analog inputs from the NASA host computer, the safety systems and the maintenance test panel, and converts them to digital signals.

The D/A card is a 16 bit converter with chopper-stabilized operational amplifiers. The interface card contains circuits for accepting NASA 28-volt logic and operating lamps. It also operates the "time to go" display.

The RSMG computer system performs three major functions:

- signal extrapolation
- safety monitoring
- maintenance

The NASA host computer provides incremental analog position and velocity command signals that are updated only every 20 milliseconds. The RSMG computer uses the velocity signal to extrapolate intermediate points every 2 milliseconds, thereby making the step change in position undetectable.

The RSMG computer is one link in a redundant safety system. It not only conducts an orderly start up or shut down, it also monitors all interlocks, limits incoming signals and performs self-checking routines. The computer supplements the maintanance control panel in aiding set-up, troubleshooting and demonstration of the RSMG system. It also contains the software to aid in setting up and checking out the computer system itself.

Safety Systems

The RSMG is designed with safety as a primary goal. Emergency systems are designed to handle three levels of potentially-dangerous situations:

- excessive commands
- subsystem malfunctions
- total loss of power

Level 1 systems are built into the electronic circuits. At the input to each electrohydraulic actuator control loop there are limiting circuits to prevent excessive commands for position, velocity and acceleration. There are also "smart" circuits for limiting the impact of running into the displacement limits of the actuators. They continuously monitor position and velocity to determine the point where the actuator must start decelerating at a safe level as it approaches the end of stroke.

Level 2 systems are those that incorporate interlocks from all critical subsystems and inputs which automatically shut the motion system down in a safely-controlled manner. Shutdown can be triggered by a variety of interlocked inputs such as:

- loss of control power
- low hydraulic pressure
- high oil temperature
- excessive system error
- operator's command
- pilot's command

Shutdown occurs in a controlled sequence. Solenoid valves close to trap the fluid in the cylinder. Excess pressure is bypassed with relief valves across the cylinder ports. When the system stabilizes the condition is analyzed and the system returned to a safe position under manual control.

Level 3 emergency systems are designed to accommodate the most severe case of failure; the complete loss of electrical and hydraulic power. For this case a set of accumulators are provided to store enough energy to return the system to a safe position. The initial action is to trap the hydraulic fluid in the cylinders by closing fail-safe solenoid valves, relieving excess pressure through the cross-connected relief valves. Also included are automatic mechanical devices on the servovalve spools that control the pressure in the accumulators to "park" the system with all cylinders retracted. These devices are programmed to move the most extended cylinders at twice the velocity of the shorter ones to avoid any hazardous attitudes on the way to the totally-retracted position.

SUMMARY

In summary, we have described the specification and design of the Rotorcraft Simulator Motion Generator (RSMG). The system is intended to replace the existing 6DOF motion generator on the NASA Vertical Motion System at Ames Research Center. The extended capabilities of the RSMG will make the VMS suitable for simulating rotorcraft as well as fixed-wing aircraft. Its performance will then satisfy the requirements of the U.S. Army's long range rotorcraft R&D programs.

The RSMG is a 4 degrees-of-freedom (4DOF) motion generator to be mounted on the 2DOF Vertical Motion System. To fit within the existing building, the RSMG was designed as a relatively uncoupled mechanical system, with independent electrohydraulic actuators for each axis of motion. The control systems have been designed especially to maintain stability and performance with a wide range of payloads. A computing system is dedicated to the RSMG to aid in signal handling, subsystem monitoring and maintenance. The entire RSMG system and its test subjects are protected by a sophisticated 3-level safety system that returns it to a safe attitude in the event of any foreseeable malfunction.

The RSMG promises to be a key element in the utilization of the VMS to implement the U.S. Army's Rotorcraft Systems Integration Simulator (RSIS).

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