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SUMMARY

Several ground-based simulation experiments undertaken to investigate concerns related to tilt-rotor aircraft airworthiness have been conducted. The experiments were conducted on the National Aeronautics and Space Administration (NASA) Ames Research Center's Vertical Motion Simulator, which permits simulation of a wide variety of aircraft with a high degree of fidelity of motion cueing. Variations in conversion/deceleration profile, type of augmentation or automation, level of display assistance, and meteorological conditions were considered in the course of the experiments. Certification pilots from the Federal Aviation Administration (FAA) and the Civil Aviation Authority (CAA) participated, in addition to NASA research pilots. This paper summarizes the setup of these experiments on the simulator, and highlights some of the results.

INTRODUCTION

The use of existing aircraft in new operational regimes or, particularly, the introduction of new types of aircraft, typically requires extension of existing design guidelines and safety criteria. To provide the data on which to base such extensions, piloted simulations—either ground-based or in-flight—of a variety of flight characteristics and operational situations are primary tools. Toward this end, NASA has historically developed and employed large motion-based ground simulators in both its internal programs to provide design guidelines and in collaborative endeavors with other agencies to provide military specifications or civil certification criteria. Examples in the civil arena include joint programs with the Federal Aviation Administration (FAA) of the United States as well as with certification authorities from the United Kingdom (CAA), Canada, and France regarding criteria for supersonic transports (Ref. 1), powered-lift transport category aircraft (Ref. 2), and helicopter instrument operations (Ref. 3).

Recent studies conducted by NASA and the New York Port Authority have concluded that a sizable market for a new class of civil aircraft—civil tilt rotors—exists. To assess the ramifications of introducing tilt rotors into the National Airspace System, one scenario includes provisional certification of a civil version of the U.S. Marine V-22 tilt rotor within the next 5 years. Accordingly, there has been renewed interest in the definition of suitable airworthiness criteria for this class of aircraft. The FAA has recently issued a revised set of interim airworthiness criteria (Ref. 4), based on 6 years of effort in updating the previous powered-lift standards (Ref. 2). However, many of the suggested criteria are based on data for configurations that are significantly different from tilt rotors, which rotate relatively large thrust devices at relatively low disk loadings to achieve the VTOL capability. Accordingly, a new joint NASA/FAA/CAA program to examine some of these operational and airworthiness questions for tilt-rotor-class aircraft was initiated, building on work begun at NASA Ames Research Center by NASA, by the FAA, and by the CAA in 1983 based on the XV-15 tilt-rotor technology demonstrator (Ref. 5), but now focused on V-22-class machines.

Specifically, the XV-15 and V-22 experiments conducted under this joint program have the following two general goals: (1) to provide data to support or modify existing airworthiness criteria for powered-lift and VTOL aircraft (e.g., Ref. 2), and (2) to provide analyses and experimental data to determine the flying qualities, flight control, and display aspects required for a good terminal-area capability, and to relate these aspects to design parameters of tilt-rotor aircraft. Toward this end, the experiments have concentrated on piloted evaluation of a number of characteristics of concern. Specific questions that have been examined include the following: Where during the approach should the conversion from wing-borne to thrust-borne flight be effected? What are the limits of the velocity-thrust-vector transition corridor? What are the influences of cross-couplings? What are the effects of representative stability and control augmentation systems? and What is the influence of display and automation enhancements? The evaluations have been conducted for representative terminal-area operations in both instrument and visual conditions by a number of test and certification pilots.

The general purpose of this paper is to summarize these experiments as examples of the way that research simulations are carried out at NASA Ames Research Center, in particular the way in which these aircraft are simulated, the manner in which the experiments are conducted, and the kind of information that is obtained. The paper is therefore organized as follows. In the next section, a summary description of the mathematical models is given, followed by sections describing the experimental apparatus, the conduct of the experiments, and a discussion of results. A few concluding remarks are then presented.

MATHEMATICAL MODELS

For the initial experiments based on the XV-15 tilt rotor (Fig. 1), the mathematical model was a generalized version of an XV-15 tilt-rotor configuration-specific model (Ref. 6). This model includes the rotor dynamics in a quasi-static sense only (no blade or tip-path-plane dynamics, linearized aerodynamics with nonuniform inflow), but contains complex aerodynamic interaction representations, through an angle of attack and sideslip range of ±180°, of such factors as downwash on the wings and fuselage, that are important for this class of vehicle. For the XV-15, a considerable effort was undertaken by NASA and the U.S. Army to provide these aerodynamic data as accurately as possible, including wind-tunnel tests of the actual XV-15 in the 40- by 80-ft wind tunnel at Ames Research Center. The model also included a detailed description of specific XV-15 characteristics, such as the engine governor and stability and control augmentation system (SCAS). For this experiment, to generalize the results somewhat, the SCAS was modified to incorporate a full-state feedback and full-control interconnect stability and control augmentation system similar to one used in a generic helicopter-simulation model used at Ames (Ref. 7). The model has a modular structure incorporating approximately 20 modules, which is intended to simplify modification tasks. One benefit of this approach is that model improvements may be made at the subsystem level while maintaining the integrity of the rest of the model. An example was the addition of generalized forces and moments programmed only as functions of velocity and nacelle angle, which were summed directly with the output of other modules representing, for example, fuselage forces and moments.

For the XV-15 experiments discussed here, the model was implemented on a Xerox Sigma model computer, which is certainly at least two generations behind the equipment currently being used. Accordingly, cycle times of the order of 60 msec were required for real-time operation. This cycle time precluded use of a good landing gear model, primarily because the high-frequency aspects could not be computed often enough, which also caused a numerical instability in the SCAS at high speed (Ref. 8).

The V-22 (Fig.2) tilt-rotor model being used in the current simulations builds upon a succession of generalizations of the XV-15 model through a sequence of "JVX" simulations in the 1980s (Ref. 9). In general, the complexity of the aerodynamic modeling is equivalent to the XV-15 version—the current version, for example, does not yet include rotor-blade dynamics. The overall model, however, incorporates a variety of more complex systems associated with the V-22, including a sophisticated SCAS that employs model-following theory with both a primary flight control system (PFCS) and an augmented flight control system (AFCS) (as in the aircraft), and a variety of envelope protection subsystems. The additional complexity of these systems and subsystems simulations are specific to the V-22, and in some cases must be deleted for the generalized simulations that are of interest for the certification work; in some instances, their complexity can even be deleterious to the understanding of the basic problems.

One such subsystem, for example, a torque command and limiting system (TCLS), uses actual rotor torque and a command value based on power-lever position, along with nonlinear saturation elements, to eliminate the need for the pilot to monitor shaft torque as he must in the XV-15 (Ref. 10). In an earlier simulation of the V-22 (Ref. 11), this subsystem produced a limit-cycle oscillation when the design gain values were used, and for reasons of expediency it was necessary to reduce a main gain to 25% of the original value in order to conduct the simulation. An extensive linearized analysis of this one subsystem was therefore undertaken for these certification simulations, including time-scaling of the responses to ensure that digital effects were not causing the problem. Again, for this simulation, the cause of the problem was not found, but the linearized analysis did indicate approaches that could improve the situation. Recently, as part of the workup for a new civil certification simulation entry, the problem was shown to result from an incorrect filter implemented on the rotor torque signal, which had been left out of the earlier analysis!

The computational machine used to run this V-22 simulation was initially a CDC 7600, which was replaced part way through the experiment with a CDC 760, the replacement being required because of damage caused by the California earthquake of October 1989. With these machines, cycle times of the order of 30 msec were achieved, and consequently an updated landing gear model was used successfully. This cycle time is also adequate to provide indiscernible "ratcheting" of electronic displays, so long as the display generation equipment can keep up. Accordingly, the limitations on the XV-15 fidelity that were imposed by inadequate cycle time are currently circumvented, although a blade-element rotor model might change that picture.

For the kind of research done in the NASA simulators, analyses based on the model characteristics are typically required, which is not the case for a training simulator; as a result, a variety of "utilities" are available. One example is the documentation of simulated aircraft in stability and control derivative form. A generalized program, available for six-degree-of-freedom rigid-body models at Ames, was modified for the tilt-rotor work to incorporate quasi-steady influences of additional degrees of freedom such as rotor rpm. Representative stability and control derivatives using this procedure were calculated for the XV-15 at three flight conditions to assist in the analysis of results and to provide the basis for generic control system improvements. Additionally, frequency-domain amplitude and phase responses can be generated and used with new frequency-domain parameter identification tools to verify simulation fidelity if an actual aircraft is available for comparison (Refs. 12,13). This last capability is critical for modern simulations, and should be required documentation for model validation.

SIMULATOR APPARATUS

Motion Characteristics

These experiments were conducted on the Vertical Motion Simulator (VMS) at NASA Ames Research Center (Fig. 3). This facility consists of a complex movable structure that carries one of several interchangeable cabs inside an eight-story building. The cabs in turn typically incorporate three or four color monitors upon which the outputs of one of two digital image generating systems are shown, as well as a flexible array of possible cockpit instrument panels and control inceptor arrangements (Fig. 4). These elements are described briefly below.

The overall motion structure consists of a beam resting on two posts that are driven through a total vertical travel distance of approximately 60 ft. The interchangeable cab then rests on an angular motion platform atop the beam, which can be driven along the beam through a total travel of approximately 40 ft. For both tilt-rotor experiments, the cab was oriented with its longitudinal axis along the beam, thereby enhancing the longitudinal cueing considered important for accelerating and decelerating transitions. Linear acceleration cueing capabilities using this orientation approach 0.75 and 0.5 g in the vertical and longitudinal axes, respectively.

For the XV-15 experiments, the angular platform consisted of a CAE "hexapod" typical of motion-base training simulators, with similar angular displacement, rate, and acceleration capabilities. In the interim between these experiments and the V-22 simulations currently under way, the angular motion platform was upgraded by adding a new device initially constructed by the Franklin Institute and heavily modified at Ames. This upgraded platform allows angular displacements in pitch and roll of nearly 20°, angular rates of approximately 40°/sec, and angular accelerations over 110°/sec^{-2}, plus a pure horizontal/translational degree of freedom. Qualitatively, pilot comments have indicated that for unstable hovering vehicles the more apparent onset of angular motion with the new facility permits stabilization by the pilot that is similar to that achievable in the real aircraft.

Visual Presentation Characteristics

These experiments place a premium on the flexibility of the computer-generated-image (CGI) equipment, because of the large number of situations that are of interest. In particular, both of these experiments considered approaches to conventional airports and to offshore oil rigs in a variety of weather and visibility conditions. For the XV-15 experiments, the image-generating equipment was a Singer-Link DIG I, the software for which has undergone considerable expansion at NASA during the past several years. This system drives four monitors to enable reasonably wide field-of-view simulation capabilities. For rotorcraft applications, however, it requires creative use of existing capabilities in order to minimize inherent polygon-drawing limitations that can result in a limited amount of detail and lack of texturing in the scene. For example, in these experiments a lack of surface wave texture, together with the monocular nature of the visual system, made it very difficult to judge height in approaches to the oil rig, even with the rig in sight. Furthermore, it was the pilot's opinion that the limited "over the nose" view from the cockpit (approximately −15°) required approaches to the rig to be flatter than they would be with a real aircraft. Because both visual and instrument conditions were of interest for certification, they too were simulated. Instrument conditions were simulated by varying the runway visual range (RVR) in the CGI computations; the instrument evaluations were conducted, therefore, in simulated fog down to breakout altitudes of 200 or 400 ft, followed by a "visual" portion to touchdown at a low RVR (0.5 mile). Visual approaches, which were conducted in basically unlimited visibility, included the use of simulated visual approach situation indicators (VASIs) located next to the runway on the CGI data base.

The V-22 simulation used a different CGI system based on an Evans and Sutherland CT-5A. As configured at Ames, this system was developed for a dome-type of presentation, and provides three channels of scene information (rather than the four of the DIG I); this necessitated some compromises when the system was used with the interchangeable cabs, which are capable of showing four channels in a monitor/beam splitter/mirror system. Specifically, approaches to the runway scene were made using the three top windows (Fig. 4), while the oil rig scene was shown in the top two right and the right chin window to provide additional vertical field of view. This system has a much higher scene-content capability than the DIG I, although—as is true with any CGI system—research requirements can still overload it, leading to, for example, "stepping" updates for high yaw-rate inputs at hover. The instrument-conditions simulation capability with the CT-5A was judged considerably superior, with excellent fog and cloud gradation capability and very good runway and area lighting simulation.

Not visible to the pilot directly, but of primary importance in the simulation of high bandwidth tasks such as rotorcraft hover and landing, is compensation for the computational delay introduced by the CGI system. At Ames, a procedure has been developed that adds computational lead to the signal sent to the CGI. This alleviates the phase lag caused by the delay over a range of frequencies important to pilot control (Ref. 14). This compensation is available for use with either of the image generating systems discussed above. Although it had not been developed in time for the XV-15 simulations, it was used in the V-22 experiment.

From the pilot's point of view, it is interesting to note the increase in simulation fidelity through the course of these experiments. In earlier helicopter tests, some noise and vibration caused by the motion system tended to degrade simulator realism. The XV-15 and V-22 simulations used sound simulation, which partially masked some of the noise, and for the V-22 simulation, the VMS building was treated with sound-absorbing equipment. In addition, the motion system upgrade mentioned above was also instrumental in reducing the vibration during the recent V-22 experiment, so fewer spurious cues were noted. Similarly, although some problems with field of view remain with the later CGI system as implemented in the interchangeable cab used for this experiment, the increased scene detail, in combination with the delay compensation, resulted in hovering performance that felt realistic to the pilots.

CONDUCT OF THE EXPERIMENTS

Task Definition

The evaluation tasks for these experiments concentrated on terminal-area operations for VTOL aircraft. The approaches were started approximately 4.5 n.mi. from the destination, at a heading simulating radar vector intercept of the localizer, at altitudes depending on the conversion profile selected for examination, but typically between 1200 and 2000 ft AGL. A 6° glide slope was used for all runs, both for visual approaches through a simulated VASI and for instrument approaches via a simulated microwave landing system. For the XV-15 experiments, task difficulty, as determined by the manner in which conversion from airborne through powered-lift to thrust-borne flight was accomplished, was one of the experimental variables. Three different ways of effecting the conversion from horizontal-thrust inclination to vertical-thrust inclination were considered: (1) all conversion from 150 knots (horizontal) to 60 knots (vertical) done in level flight before acquisition of the 6° glide slope (profile A); (2) partial conversion to 60° inclination at 110 knots before the glide slope, the remainder when tracking the glide slope (profile B); and (3) the entire conversion performed while tracking the glide slope (profile C). In the first phase of these experiments, the instrument task concluded with a breakout to visual conditions at 60 knots, followed by a flare to a 30-knot run-on landing; in the second phase, however, this part of the task was made considerably more difficult by requiring a deceleration on instruments to about 25 knots and then a further deceleration after breakout to hover and a vertical landing.

The V-22 simulation carried forward an investigation of these three conversion profile ideas for numbers that were appropriate for that machine. Accordingly, the initial airspeed was 180 knots, and the intermediate condition at 60° thrust inclination corresponded to 120 knots. Most important, the final part of the approach was again made more complicated.

On the premise that the final speed should be higher than 60 knots to permit a better mix with other terminal-area traffic, a value of 80 knots was selected; although a variety of combinations of thrust inclination and nose attitude can yield equal airspeeds for this class of vehicle, to achieve a near-level fuselage attitude required that the thrust inclination for this velocity be 80°. Accordingly, in order to effect a slow run-on or vertical landing, an additional configuration change was now required at the bottom of the approach, with a nominal thrust-vector change to 90° and concomitant deceleration to about 30 knots before touchdown.

As was mentioned earlier, to evaluate these operations in reasonable environmental conditions requires the simulation of winds and turbulence in addition to obscured visibility. Accurate models of the wind and turbulence at low altitude are still more a desideratum than a fact, particularly for VTOL aircraft and rotorcraft for which the flight airspeed changes drastically. At Ames, the generic wind/turbulence model uses a conventional Dryden or von Karman turbulence model in conjunction with winds that may incorporate a linear shear. For more specific simulations, particularly for transport CTOL aircraft, more extensive wind-shear modeling is available, as are actual microburst wind-shear data. For these experiments, the generic model was used. The XV-15 experiments included 10-knot headwinds with light turbulence (~2 knots rms) or a 10-knot crosswind with moderate turbulence (~4.5 knots rms); the V-22 levels were similar, although the 10-knot headwind was replaced with a 5-knot crosswind with light turbulence. As previously mentioned, the XV-15 visual conditions included a 400-ft ceiling with 1-mile visibility under it, and a 200-ft ceiling with 0.5-mile visibility; in the V-22, the values were 200 ft with a 2000-ft RVR and 100 ft with a 1000-ft RVR.

Evaluation Procedure

In these experiments, the Cooper-Harper handling-qualities rating scale (Fig. 5, from Ref. 15) was the primary means of assessing the suitability of the aircraft characteristics for the selected task. The proper use of this scale, in either a flight experiment or, particularly, in a simulator experiment, is necessary if consistent results are to be achieved. A lack of training with either the aircraft or in the use of the scale can lead to undesirable variability in the results. As can be seen in Fig. 5, the rating that the pilot assigns is determined by first ascertaining whether the workload-performance combination of the aircraft is satisfactory, unsatisfactory but adequate, or inadequate. In general, the difficult choices involve determining whether the performance that was achieved is the level desired, and the extent of pilot compensation required to take care of the aircraft deficiencies. Accordingly, great care must be taken in assigning required levels of performance and in reaching agreement among the pilots as to what those levels are. In these experiments, desired glide-slope and localizer tracking performance has been set at ±1 dot on the instrument, with adequate being ±2 dots. Although a direct connection between the ratings assigned using this scale and a pilot's assessment of whether an aircraft is certifiable is really not possible, ratings that fall between 4 and 5 would indicate desired performance although at higher than moderate compensation levels, and would probably represent a minimum certification standard.

A significant amount of training was necessary at the beginning of each experiment to familiarize the pilots with the characteristics of the tilt-rotor and to teach some of the certification pilots the use of the Cooper-Harper scale. In the XV-15 experiments, the certification pilots had no tilt-rotor experience, but NASA tilt-rotor pilots also participated and assisted in familiarization aspects. No NASA pilots participated directly in the V-22 experiment, a result of schedule conflicts. The previous two certification pilots were again subjects, however, and seven other pilots also participated. Additionally, the seven new pilots were not familiar with the use of the Cooper-Harper scale. Accordingly, the rating scatter among the pilots was higher in this experiment than would be expected, and the results will need to be confirmed or modified in future endeavors.

One way to reduce the influence of learning and of the "saturation" of the pilot that is sometimes caused by the large number of configuration changes, is to give each pilot a datum test configuration to which to relate. In the XV-15 experiments, each simulator session was commenced with the pilot formally reevaluating the known datum and assigning a rating; this value was compared with previous ratings, and used interactively to "calibrate" the pilot. This procedure was not followed consistently in the V-22 experiment because of time constraints, and hence the inconsistency of the evaluations caused by inexperience was exacerbated.

Finally, from the pilot's point of view, a very natural tendency that had to be guarded against during these experiments was the desire to modify the task in some way to compensate for poor vehicle characteristics. An example particularly germane to the tilt rotor is a tendency to want to start a conversion when below the glide slope, since both the XV-15 and V-22 exhibit a marked tendency to "balloon" during conversion. To help guard against this tendency, the pilots described the characteristics of each approach immediately afterward with reference to a comment card; procedures that seemed to be different could then be ascertained by the research team and discussed.

DISCUSSION OF SELECTED RESULTS

For the purposes of this discussion, it is simplest first to discuss results from the XV-15 experiments that concern the influence of the conversion procedure, and then to compare these specific results with those obtained recently for the V-22. Results relevant to the conversion corridor and force/moment coupling were examined only for the XV-15 to date; they are discussed in Ref. 5.

Therefore, first consider the XV-15 pilot rating results given in Fig. 6. Note that the figure includes data for two sets of wind/turbulence conditions, two visual environments, and two aircraft augmentation systems, all of which were easily included as variables because of the flexibility of the simulation facility. In visual conditions and light turbulence, the less complex rate-based SCAS received ratings in the satisfactory category for the profiles in which all or part of the conversion was accomplished before glide-slope acquisition (profiles A and B). Typical problems included substantial nose-down trim-change requirements through the conversion, and significant ballooning above the desired glide path. Because most of the conversion occurred before the descent for these two profiles, however, these difficulties were not considered to degrade performance below the desired level. When all the conversion was performed while descending (profile C), the ballooning above the desired flight path occurred later in the approach. This degradation in precise flight-path control, coupled with the additional workload involved in getting the entire conversion completed in time to be properly set up for the final flare, was noted in the pilot comments as the reason for the drop in the average rating to the adequate-but-not-satisfactory category.

As can be seen by the data (Fig. 6), adding an attitude-command SCAS to the XV-15 provided control characteristics that improved the situation considerably. The pilot comments indicated that the major improvement was in longitudinal predictability, so that the ballooning could be counteracted more easily. Accordingly, the ratings indicated that desired performance could now be achieved for all profiles in visual conditions.

In general, therefore, the results for a visual approach in light turbulence indicated a minimal influence of conversion profile for the XV-15, regardless of SCAS type. As can be seen from Fig. 6, more severe environmental conditions, simulated by a higher turbulence level, meant that desired performance could not be achieved with the rate SCAS when all of the conversion had to be performed while descending on a visual approach. Here again, however, implementing the more complex attitude-command SCAS improved the aircraft characteristics sufficiently for the pilots to again achieve desired performance for all three profiles.

For the XV-15 instrument approaches, the pitch-control and conversion-induced coupling problems were strongly influenced by the profile. If all the conversion was performed before the glide slope was attained (profile A), the ratings generally indicated that desired performance was still achievable, although at the expense of considerable pilot compensation, with the attitude system again providing some improvement. With the partial conversion on the approach (profile B), the ratings with the rate-SCAS deteriorated considerably, particularly in the higher level of turbulence. Here, the ballooning caused by even the partial conversion did cause a degradation in performance that was not evident in visual conditions. For this profile, the attitude SCAS was of significant benefit for instrument approaches because the pilot's attention to attitude control could be reduced. When all of the conversion was performed on the glide slope, the ratings and comments demonstrate that with the basic rate SCAS, the XV-15 was marginally inadequate for the task in the less turbulent conditions, and was inadequate in the higher turbulence. Here, even the lateral-directional performance started getting away from the pilots because of the need to concentrate so heavily on glide-slope control. Now the task was becoming so difficult that even with the attitude-command SCAS, adequate performance at best could be achieved. It is worth pointing out that this profile with a raw data display is operationally very difficult, and that some of the variations in flight-characteristics were beginning to be washed out by this degree of difficulty.

Some of the V-22 results are compared with the XV-15 results in Fig. 7. This comparison must be interpreted with care because the environmental conditions were not exactly the same (although close), and the V-22 SCAS as simulated incorporated attitude-command only in pitch, with rate-command-attitude-hold in roll rather than the attitude command designed for the XV-15. Previous work has indicated, however, that these differences should have had only a minor influence on the results for the levels of augmentation and turbulence considered. As can be seen, the V-22 trends duplicate those found earlier in the XV-15 experiments. In particular, as the requirement to perform more of the conversion while descending is placed on the pilot, the suitability of the system degrades, as it did for the XV-15. The actual results are in surprisingly good agreement for the instrument approaches, but the pilots in the V-22 experiment typically rated the V-22 worse for the visual approaches than the XV-15 had been rated previously. According to the pilot comments, a possible concern with the V-22 as simulated was the use of a fore-aft "power" controller. In contrast, the XV-15 uses a conventional up-down collective controller. These pilots were helicopter certification pilots, used to a collective for vertical control, and the training required to adapt to the fore-aft controller was difficult to accomplish in the limited time available. It is possible that this characteristic is responsible for the poorer average ratings in visual conditions.

It is apparent from the data for both vehicles that instrument operations employing thrust-vector conversion are going to have to provide some additional assistance to the pilot to achieve ratings in the "satisfactory" category. One aspect of such assistance was examined in the XV-15 experiments. Because the data shown previously are for an aircraft in which the pilot performs the conversion manually, and in which raw-data-only displays were used, the flexibility of the simulation setup was exploited to consider addition of an automatic conversion and the implementation of three-cue flight director displays. The results for instrument approaches with profile C, requiring all conversions to be accomplished on the glide slope, are shown in Fig. 8. It is apparent that significant improvements in average rating may be obtained with the automation and display enhancement, and ratings approaching the "satisfactory" category were in fact obtained for this most difficult conversion profile. In current work with the V-22 simulations, this aspect of the problem is being examined by comparing the flight director display with a new head-up flight-path-oriented electronic presentation.

CONCLUDING REMARKS

A research simulation facility embodying a high degree of motion-cueing capability for rotorcraft and VTOL-class aircraft has been used in a study of airworthiness considerations for tilt-rotor aircraft. Both light and transport category aircraft were simulated, and variations in conversion procedure, conversion corridor, and conversion coupling to other axes were considered. Simulated tasks included both visual and instrument approaches to airfield and oil-rig landing areas, with the approaches incorporating conversions from 150 to 60 knots and from 180 to 80 knots. Approximately 400 evaluations by 10 pilots have been obtained to date.

Based on these experiments, the following conclusions may be drawn:

1. In visual conditions, the influence of the conversion profile was minor for the XV-15. Increasing the proportion of the conversion that was performed during the descent resulted in a slight decrease in capability for the V-22. This result was not particularly influenced by the type of stability/control augmentation implemented for the range that was studied.

2. In instrument conditions, the conversion profile had a significant influence on the degree of pilot acceptability. In particular, with raw-data displays and manual conversion, even with an attitude-command augmentation, a barely adequate capability resulted if all of the conversion was performed while descending.

3. The instrument approach results for the XV-15 with an attitude-command system and for the V-22 with a similar system in pitch were nearly identical.

4. With an attitude-command augmentation system, there is a significant improvement in instrument approach capability when an automated conversion in conjunction with a three-cue flight director display is added.

5. The VTOL class of vehicle amplifies the interaction between the aircraft's stability and control characteristics and the required operational situation for civil operations. For operations similar to those for aircraft, in which no configuration change is necessary during the descent, less airframe/systems capability of the tilt rotor is required than for operations that exploit its VTOL capability by including a conversion from airplane to helicopter mode late in the approach phase.

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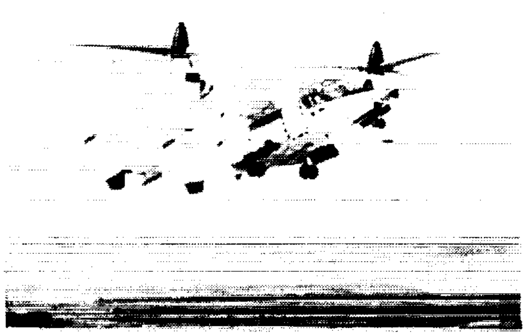

Fig. 1 XV-15 tilt rotor.

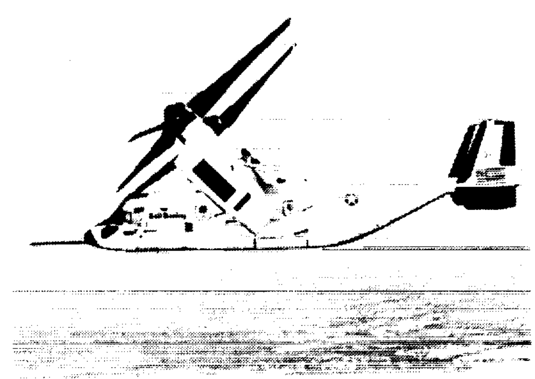

Fig. 2 V-22 tilt rotor.

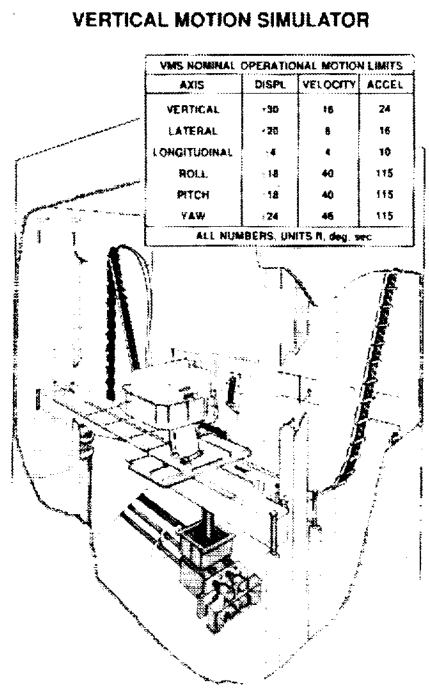

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Fig. 3 Vertical motion simulator.

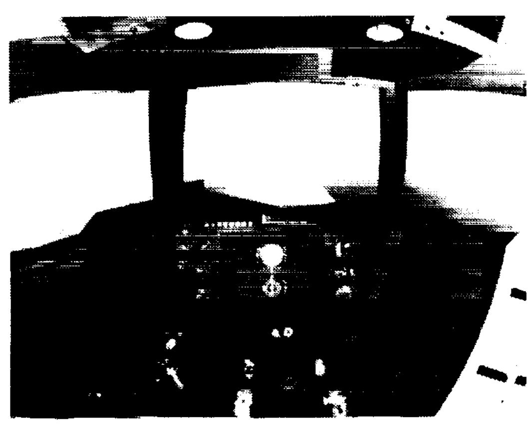

Fig. 4 Simulator cab.

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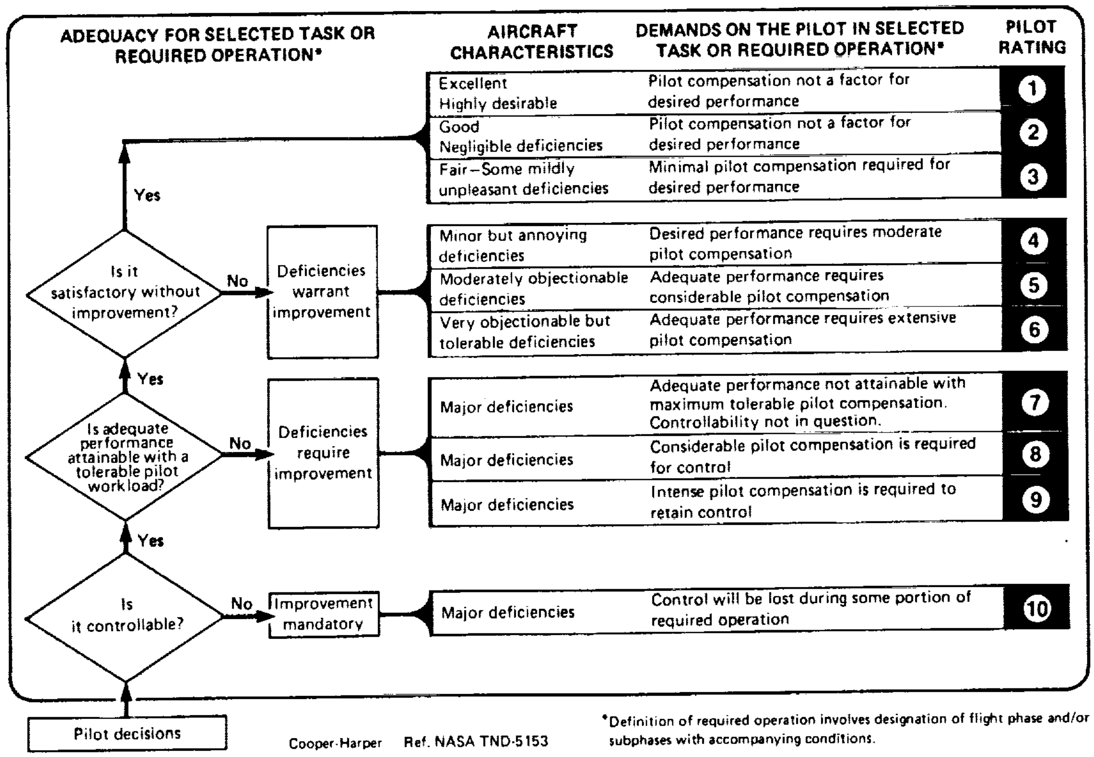

Fig. 5 Cooper-Harper Pilot Rating Scale (from Ref. 15).

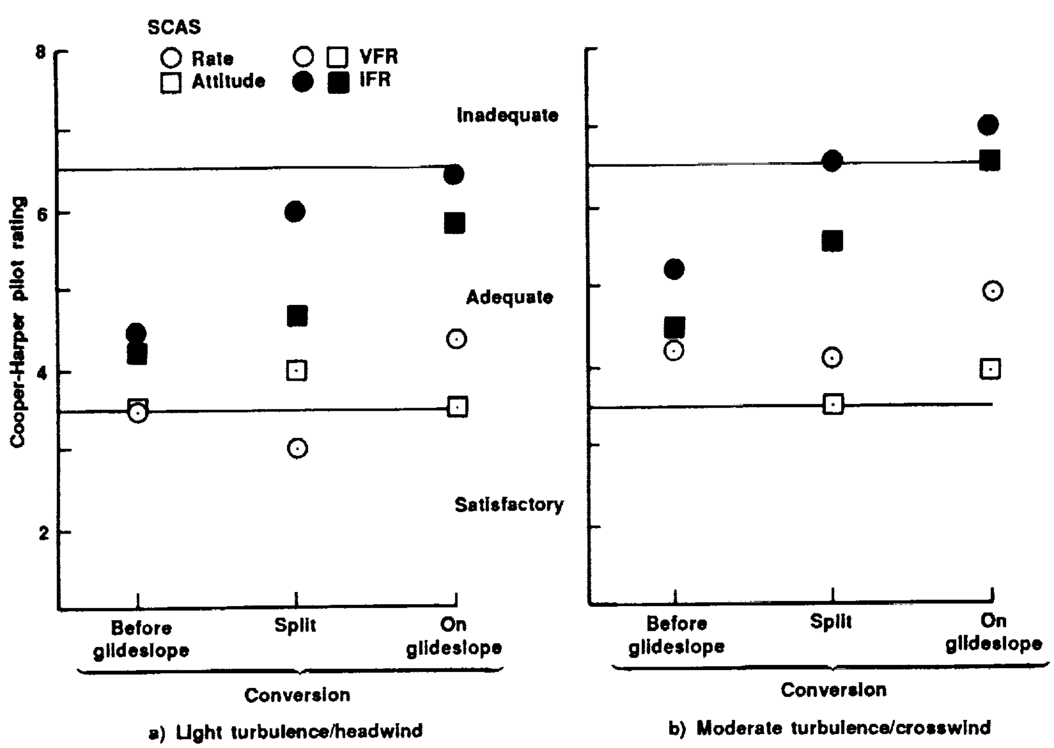

Fig. 6 XV-15 pilot rating results.

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Report Documentation Page

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15. Supplementary Notes

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16. Abstract

Several ground-based simulation experiments undertaken to investigate concerns related to tilt-rotor aircraft airworthiness have been conducted. The experiments were conducted on the National Aeronautics and Space Administration (NASA) Ames Research Center's Vertical Motion Simulator, which permits simulation of a wide variety of aircraft with a high degree of fidelity of motion cueing. Variations in conversion/deceleration profile, type of augmentation or automation, level of display assistance, and meteorological conditions were considered in the course of the experiments. Certification pilots from the Federal Aviation Administration (FAA) and the Civil Aviation Authority (CAA) participated, in addition to NASA research pilots. This paper summarizes the setup of these experiments on the simulator, and highlights some of the results.

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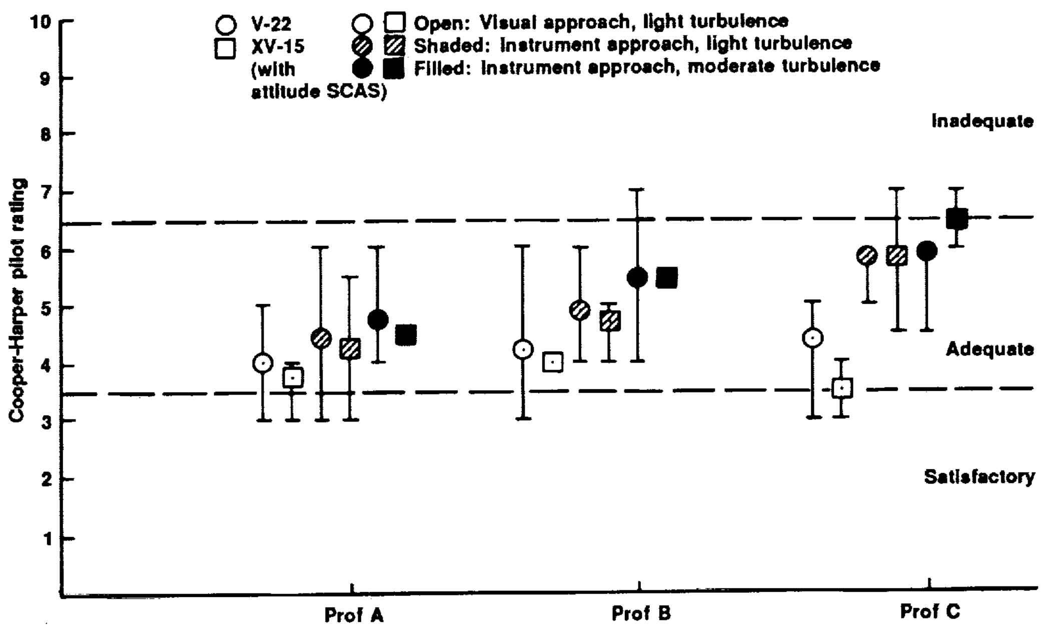

Fig. 7 Comparison of XV-15 and V-22 results.

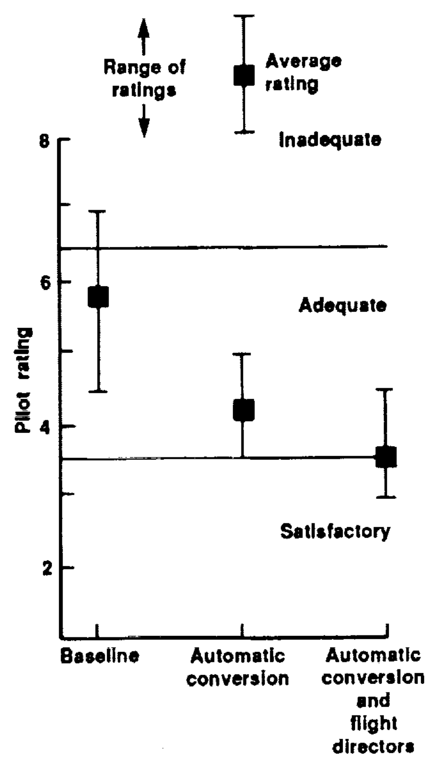

Fig. 8 Influence of automation and display assistance.