thereby returning the bogie pitch position control to the first stage operation of the pneumatic centering spring.

Conclusion

In the course of finding solutions for the C-5A main landing gear bogie pitching control problems, the following design techniques were applied.

Separation of functional requirements: Three major functions were defined, namely, bogie pitch angle pattern in gear retraction/extension, pitch angle range for on-ground operation, and pitching stabilization during application of wheel brakes. Damping to minimize oscillation was also identified. Design approaches were then selected with respect to the compatibility of the requirements. Two-stage operation of the pitch positioner is an application of this technique.

Re-evaluation of the objectives: When it was apparent that full compensation of the braking torque at all times could be achieved only at the expense of excessive weight and complexity by the conventional design approach, a re-evaluation of the design objectives showed that slight modification of the objectives would allow a much simpler and lighter design. Consequently, a single torque compensating rod is utilized to stabilize the C-5A main bogie which has six wheel brakes. The reduction of 0 to 6% braking effectiveness is hardly noticeable in the braking performance of the multiple brakes and yet the resultant mechanization is definitely simple and light occupying very little space.

Utilization of common components: The advantages are obvious. The bogie pitch positioner does not require an anchor point on the shock strut relieving a space congestion problem in that area. This is made possible by utilization of the braking torque compensating mechanism.

Utilization of environment: The bogie pitch positioner is designed as a self-contained unit. This is so by the utilization of a guide track in the wheel well to accomplish the bogie pitch position control in the retraction/extension operation. The track is also used to trigger the second stage operation of the positioner relieving excessive loads to the retraction mechanism and the associated structure.

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Requirements on Simulators Used in Handling Qualities Research

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A methodology has been developed for driving the visual display and motion systems of a large-amplitude and rotational 3-axis flight simulators to minimize the impact of the constraints of pilot subjectivity and task dependence. In explaining the drive technique, a simple model of the sensing mechanisms of the vestibular system is used. However, a way has not been found yet to take advantage of the vestibular system description to establish the dynamic performance required of the elements in the motion and visual display system. The success of the drive scheme depends on subjective observations of test pilots which allow filters used in the drives to be properly set in terms of gain and break frequency; the filter characteristics also are task-dependent. Experiments conducted on the simulators provide some assurance that the drive technique works within these constraints. The first of a series of experiments being conducted on the large-amplitude, 3-axis simulator to develop a rationale for motion and visual display drives for moving base simulators is discussed in which a comprehensive simulation of the Cornell T-33 inflight simulator has been mechanized. Flight experiments have been repeated on the simulator. Results of this work suggest that a mix of simulators be used to study the problems associated with fighter-bomber mission effectiveness and handling qualities.

Nomenclature

$G(\omega)$ = amplitude ratio
$<G(\omega)$ = phase angle
ω = frequency
Z beam = beam vertical displacement
$\dot{Z}$ beam = beam vertical velocity
$\ddot{Z}$ beam = beam vertical acceleration
K = gain
τ = time constant
S = Laplace operator
ϕ = bank angle
$\dot{V}_{co}$ = lateral acceleration
$\dot{U}_{co}$ = forward acceleration
m = mass
θ = pitch angle
N_Z = vertical load factor
N_T = lateral load factor
ζ = damping ratio
ω_n = natural frequency
$|\phi/\beta|$ = roll to sideslip ratio
N_p' = yawing moment due to roll rate
δas = aileron stick input
$N'_{\delta AS}/L'_{\delta AS}$ = yaw to roll ratio of lateral controls
$L'_{\delta AS}$ = rolling moment due to stick input
F_{AS} = aileron stick force

Presented as Paper 70-353 at the AIAA Visual and Motion Simulation Technology Conference, Cape Canaveral, Fla., March 16–18, 1970; submitted April 6, 1970; revision received June 1, 1971. The work on which the discussion in this paper has been based has been accomplished with the assistance of W. W. Koepcke, R. L. McCormick, J. B. Sinacori, and T. E. Mehus in the Vehicle Dynamics and Control Research Branch at Northrop.

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Introduction

ADVANCES in simulator hardware capability and electronic computer technology have improved the simulation of flight vehicles and their environments. This has come at a time when simulations of fighter and attack aircraft are centered on reproducing total mission segments, i.e., accurately reconstructing the air-to-ground weapons delivery, air-to-air engagement, low-altitude penetration, and (for the future) short and/or vertical takeoff and landing segments of the mission. It is improbable that all of these mission segments can be accomplished on a single ground-based simulator. In any case, a common weakness of ground-based simulators is an inability to present motion and visual cues propertly to the pilot. Our discussion of Northrop's simulators and experiments conducted on them will show that useful simulations can be conducted, but their success depends on the subjective observations of the pilots regarding the correct method of washing out rotational and translational motion stimuli. The washout techniques are also task-dependent. A series of experiments that is being conducted to establish a quantitatively sound method of driving the simulators and to provide a catalogue of washout characteristics which are task-related will be discussed.

An external view of the Northrop 3-Axis Large Amplitude Flight Simulator (LAFS) is shown in Fig. 1. This moving base simulator employs a gimballed cockpit suspended at the end of a beam; the three rotational degrees of freedom are obtained through the gimbals. The beam is pivoted on a clevis and driven by front and rear hydraulic actuators to provide vertical translation. Laterial translation is derived through a pivoting mechanism between the clevis and the post, driven by hydraulic actuators. A satisfactory level of fidelity in the output characteristics of the simulator response is simulated[1] within the limitations imposed by the following constraints: 1) available hydraulic power imposes magnitude limits on acceleration and velocity motion response; 2) total travel of the simulator sets limits on displacement; 3) the motion control servo sets upper and lower limits on the dynamic response of the simulator; and 4) Coulomb and breakaway friction exists in the output of the servodrive.

Figure 2 shows a typical response of the simulator translation motion system to sinusoidal inputs and indicates how velocity saturation sets amplitude limits on motion response over midrange frequencies. Acceleration saturation determines amplitude limits at high frequencies, and position saturation sets displacement limits at low frequency. The visual display system of the moving base simulator consists of servoed transparency projectors for horizon and target. Each of these displays is used to backlight a large screen located in front of the cockpit.

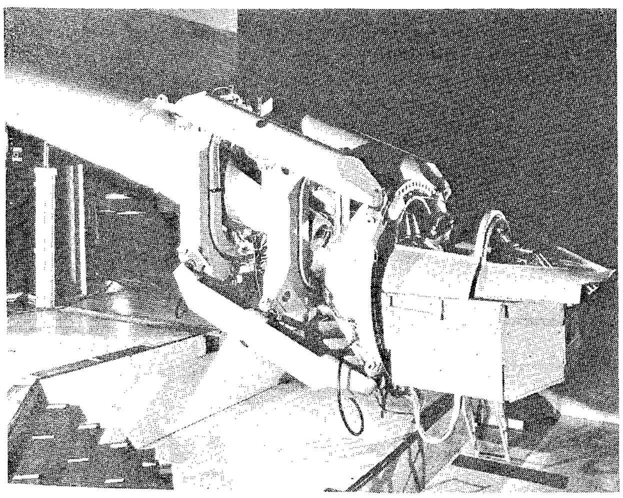

Fig. 1 Large amplitude 3-axis flight simulator.

A general view of the Northrop Rotational 3-Axis Flight Simulator (RFS) is shown in Fig. 3. Hydraulic actuators supply pitch, roll, and yaw rotations to the cockpit. The limitations on satisfactory fidelity of simulation motion response are, as with the LAFS, available hydraulic power, total travel, motion control servo limitations, and the coulomb and breakaway friction. Figure 4 shows a typical frequency response of the simulator rotational motion system. The visual display system is a version of the 6-degree-of-freedom, De Florez point-light-source visual display. The display hardware is located within a 12-ft-radius hemispherical screen (Fig. 3). Its frequency response is characterized by a bandwidth similar to that of the motion base as indicated for the pitch attitude in Fig. 4.

Motion System and Visual Display Drive Technique

In general, any technique used to drive the motion system and visual display should result in the proper presentation of visual kinesthetic and vestibular stimuli to the pilot, but there are two basic difficulties: 1) a lack of understanding of how the pilot assimilates information on the state of his aircraft in its environment, and 2) an inability to reproduce the stimuli used in the assimilation process because of the physical capability of the equipment being used. The most expedient method of overcoming these difficulties is to develop a simulation technique based on subjective valuation of simulation fidelity by experienced pilots. The concept used to drive the LAFS and the RFS will be discussed to show the level of subjectivity involved.

Drive Philosophy on the Large-Amplitude 3-Axis Flight Simulator

The most significant physical aspects of the LAFS affecting the methods of providing the correct visual and motion cues are: 1) the visual display is not carried on the motion system, and 2) the motion system is displacement limited in the translational degrees of freedom. As a result, the satisfactory application of the simulator in handling qualities research requires a very sophisticated drive technique. The visual display is mathematically "carried" with the motion system

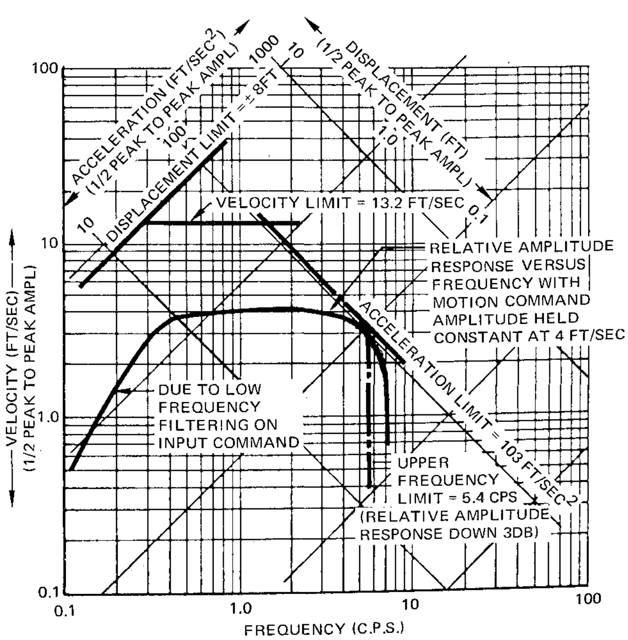

Fig. 2 Response of vertical translated motion system at pilot's station to steady sinusoidal motion.

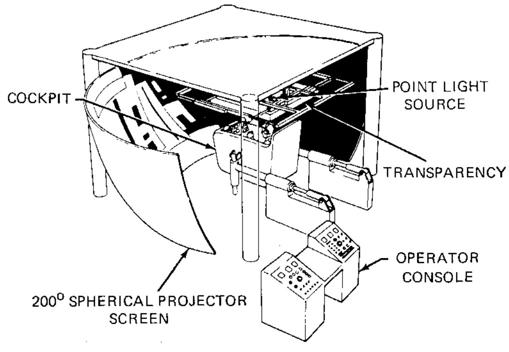

Fig. 3 Rotational 3-axis flight simulator.

through the transformation matrices relating the Earth and the screen axis, the X axis of the aircraft and the pilot's line of sight, and the pilot's eye distance to the projection screen. Elements of these matrices process the beam command washout signals, the cockpit command washout signals, and the beam and cockpit position feedback signals. This slaving of the display information to the motion information prevents any discrepancy between the visual-sensed and body-sensed motion information.

There remains a more subjective problem—that of providing correct motion stimuli to the vestibular system given a displacement-limited motion system. Taking some liberties with the information in Ref. 2, it is possible to think of the vestibular system as a system capable of sensing changes in rotational attitude and translational acceleration with the bandpass characteristics as shown in Fig. 5. The rotation-sensing is apparently handled by the semicircular canals, and the translational motion sensing is handled by the utricles; this simple model of the motion-sensing capability of the vestibular system is used in developing a drive technique for the simulator.

Figure 6 shows a block diagram of the motion base and visual display drive system, and particularly shows the flow of low-frequency signals. The dashed lines indicate the signal flow. For example, the low-frequency content of the θ signal is shown flowing directly to the visual display while not being passed by the high-pass filter (block 2) when attempting to get to the motion base.

Block 1 of Fig. 6 contains the washouts necessary to process the translational motion cues in a manner to provide onset acceleration cues while avoiding commands that would cause the displacement limits of the simulator from being exceeded. The washout is normally a high-pass filter designed to match the high-pass characteristics of the body sensors. The break frequencies are set subjectively by evaluation pilots and are normally such that certain prescribed tasks can be accomplished without nuisance disconnects of the drive system. In general, for tasks associated with low-frequency maneuvering such as dive bombing, single-break washouts are used, whereas for tasks with high-frequency inputs such as low-altitude, high-speed flight, double washouts are provided.

Block 2 of Fig. 6 contains the washouts sometimes necessary in processing angular attitude motion cues. The need

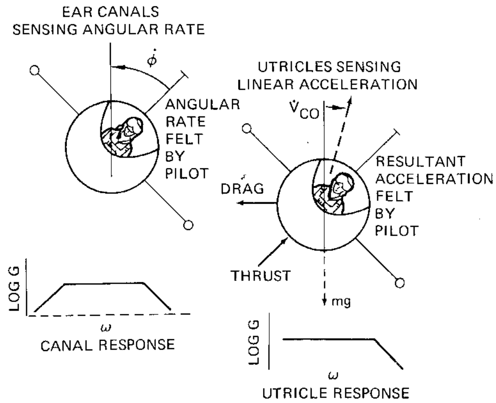

Fig. 5 Simplified model of vestibular system.

for the washout is seldom to avoid displacement limits but to avoid postural inconsistencies in a device that has insufficient translation capability to provide correct simulation of a specific force. The high-pass characteristic is normally matched to the high- and mid-frequency characteristics of the semicircular canals. At this time, the only successful method of setting the break frequency is through subjective pilot evaluation and is heavily task-dependent.

An interesting thing that is done in this loop and appears highly satisfactory is to share rotational information cueing between the motion base and the visual display. This can be done whether washout is found necessary or not. It is easiest to see this if the motion and display outputs are inspected in response to a step attitude command. Figure 7 shows how the display takes on the total attitude command as the cockpit is washed back to level position. An unfortunate aspect of this is that simulation of gust responsiveness in the rotary motions is not precisely correct. The reason is that the pilots sense gusts through the motion system rather than the visual display and are unable to control them to their satisfaction because a proportion of their control input is going directly to the visual display and is not available in the motion loop. However, for most applications the technique has seemed satisfactory and inspection of Fig. 6 shows how, in general, the low-frequency signals do not get to the motion system but are handled by the visual display. It is felt that this is consistent with the manner in which the pilot normally processes low-frequency information.

Block 3 of Fig. 6 performs a significantly important function on this type of simulator, particularly in the lateral degree of freedom. As noted previously, Block 1 is used to filter out the low-frequency translational inputs. It is this frequency range of those signals which normally provides information to the pilot that his specific force is properly located. It has been found possible to stimulate synthetically the utricles through attitude changes and hence provide some low-fre-

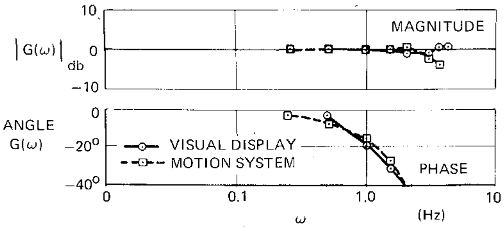

Fig. 4 Simulator frequency response.

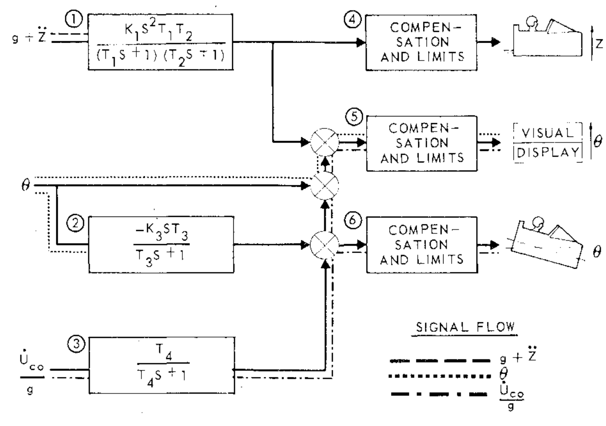

Fig. 6 Large amplitude flight simulator vertical plane motion drive scheme: low-frequency signal flow.

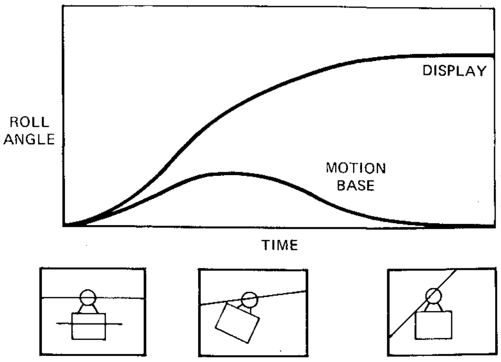

Fig. 7 Distribution of motion and visual stimuli.

quency translation cues to overcome this deficiency. The filter-break frequency nevertheless must be set to not only provide proper stimulus to the utricles but to avoid improper stimulus of the semicircular canals. Fortunately, the semicircular canals do not process low-frequency information as shown in Fig. 5, while the utricles require low-pass stimuli. The synthetic utricle stimulus must not only be passed to the rotational motion system, but also to the visual system to avoid an improper stimulus to the eyes.

Summarizing, then, with reference to Fig. 6, the translational acceleration is normally captured at low frequencies and does not get to the visual or motion systems. The attitude changes are blocked at low frequencies from the motion system and portrayed on the visual display while synthetic low-frequency translational cues are provided through the attitude motion system.

Figure 8 shows a block diagram of the motion and visual display system of the simulator and indicates the flow of high-frequency information. The high-pass filter characteristics of Block 1 pass the load factor signal, and this is carried to the motion system. The same signal is carried to the visual perceptors. By using motion system feedback signals to perform this function, (not shown on the diagram) effective slaving of the vision and motion system is achieved. This not only provides proper cueing, but avoids computational or equipment drift from affecting the accuracy of information presentation. The high-frequency attitude-change information is processed in a similar manner. The slaving block, Block 2, which controls not only the distribution of information between the motion system and the vision system but also the frequency of the signals allowed to pass to the motion system, passes the high-frequency signals to the motion base and removes a proportion of the total signal going to the visual display to avoid improper stimulus of the vision system. At the higher frequencies, there is no need for artificial

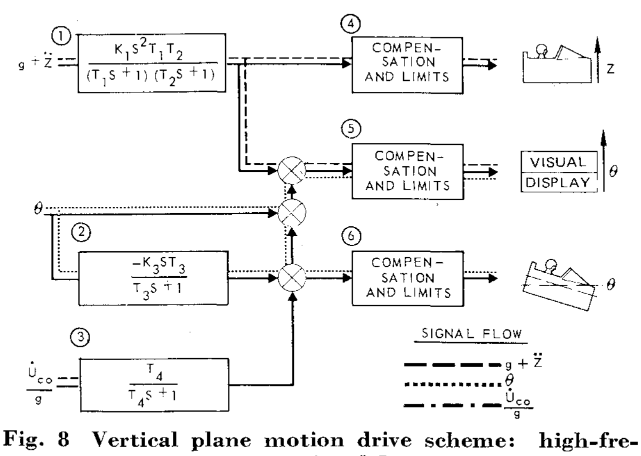

Fig. 8 Vertical plane motion drive scheme: high-frequency signal flow.

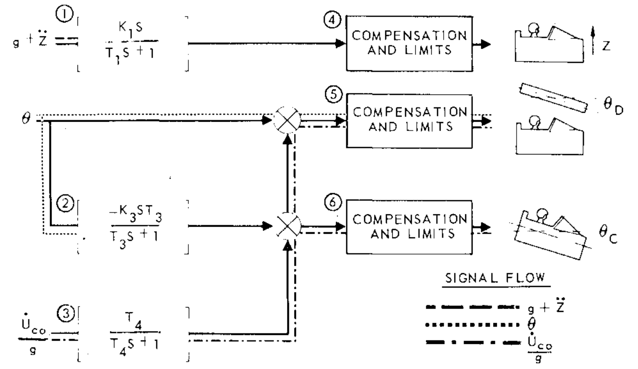

Fig. 9 Rotational flight simulator vertical plane motion drive scheme: low-frequency signal flow.

stimulus of the utricles and effective blocking is provided by the filter represented by Block 3.

Summarizing then, with reference to Fig. 8, the translational acceleration is passed to the beam motion system and visual display system. The high-frequency attitude changes are passed to the cockpit motion system and visual display system and no artificial stimulus is provided.

Perhaps the most important aspect of the technique used to drive the LAFS is the need to set the filter break frequencies at levels which are determined subjectively through pilot opinion and are dependent on task. That it works effectively is attested to by the result of an experiment discussed later; but that it leaves something to be desired is obvious.

Drive Philosophy on the Rotational Flight Simulator

The most significant physical aspects of the RFS affecting the provision of proper motion and visual cues are the same as for the LAFS: 1) the visual display is not carried on the motion system, and 2) the motion system is displacement limited in the translational degrees of freedom. However, two things distinguish it from the LAFS: a) the visual display system cannot be slaved to the motion base, and b) the motion system is severely displacement-limited in the attitude degrees of freedom. The general methodologies of driving the two simulators are the same.

Since the visual display cannot be slaved to the motion base without increasing the separation between the pilot's eye and the point light source, long-term drift can occur and difficulty arises in providing translation motion cues without imparting an improper attitude stimulus. Often it is found necessary to avoid providing translation acceleration cues through the motion base for this reason. Because of this, further discussion on the RFS will presume that no translational motion is imparted through the motion base, and only attitude motion cues are provided by the motion base.

Figure 9 shows the flow of low-frequency signals to the motion and visual display system on the RFS. Comparison with Fig. 6 shows how the slaving path between the motion base and visual display has been eliminated. Aside from this path, the drive techniques are identical to those used on the LAFS. The low-frequency translational acceleration and attitude signals are blocked from the motion base. Low-frequency attitude information is portrayed by the visual display system and, although not shown, so is the translational velocity and displacement information. The need for the high-pass filter in the altitude loops (which was to avoid postural inconsistency in the LAFS) is needed in the RFS to avoid exceeding the rotational displacement limits. The RFSis severely attitude-limited, both at the motion base and visual display system requiring this high-pass filtering. Again, as in the LAFS, artificial stimuli of the utricles are provided through the low-frequency attitude path shown, with

Table 1 Pilot rating (Cooper scale)

	Airplane 1	Airplane 2	Your airplane
Response to control inputs			
Elevator	2	2	2
Aileron	2	2	3
Rudder	1	1	1
Ability to perform			
Terrain following	1	1	3
Heading holding	2	2	2
Establish and maintain straight and level flight	3	3	2
Stick forces			
Elevator	2	2	2
Aileron	2	2	3
Rudder	1	1	2

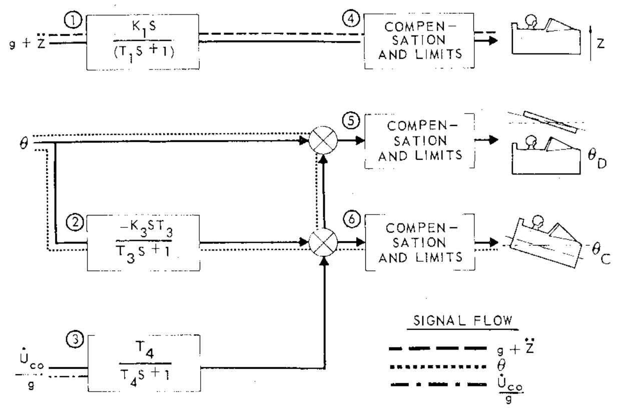

Fig. 10 Vertical plane motion drive scheme: high-frequency signal flow.

compensating information flowing to the visual display to prevent improper stimulation of the visual perceptory system.

Figure 10 shows the flow of high-frequency signals. As observed previously, the translational cockpit motion is seldom used, since the translation of the motion base cannot be matched by the visual display system without increasing the separation between the pilot's eye and the point light source. The high-frequency attitude changes are normally sent to the motion base and by judicious choice of filter break frequency and gain, high-frequency inputs are kept from the visual display. It is important that this blocking occur because of the structural sensitivity of the transparency used in the visual projection system.

In summary, low-frequency attitude changes are high-pass filtered and passed to the visual display system. Artificial stimulation of the utricles is provided through low-frequency filtering of an attitude signal proportional to the computed translational acceleration force. High-frequency attitude information is blocked from the visual display and handled through the motion base. Translational acceleration stimuli are seldom provided through the motion base, and translational displacement and velocity are portrayed by the visual system. Again, the most important aspect of the drive technique is the need to set the filter break frequencies at levels which are determined subjectively through pilot opinion and are dependent on task. The experiment discussed later indicates that the technique provides adequate simulation when the tasks have a low-translational acceleration content and the attitude displacements are low.

Typical Simulator Applications

AMSA Ride Quality Simulation

The objective was to investigate systematically the interaction effects of terrain, gusts, vehicle gust responsiveness, and mission duration on crew performance during a simulated low-altitude, high-speed mission in a flexible airplane, e.g., the Advanced Manned Strategic Aircraft, AMSA. There was no attempt to establish crew tolerance limits or maximal environmental parameters. Instead, the study was undertaken to determine expected levels of performance as influenced by the environmental variables. A fixed-base simulator was used for the portion of the flight away from the low-altitude environment, and the LAFS was used for the low-altitude penetration and weapons delivery.

A typical power spectrum for the vertical load factor, resulting from gust and maneuver inputs, measured at the crew station during low altitude flight indicates the energy levels recovered by the simulation (Fig. 11). Notice the loss of energy at the lower frequencies associated with terrain following, and the attentuation at high frequencies due to the reduced simulator hydraulic actuator transmissibility. In the case of the lateral acceleration (coordinated turns), a great deal of the total gust and maneuver energy is recovered by the simulator.

As well as the recovery of energy at the crew station, an important aspect of the simulation was to provide a feel to the simulator that the pilots would associate with an actual airplane. In general, the pilots rated the simulated AMSA (and the simulated VTOL airplane, discussed later) as comparable with their own combat airplane as shown in Table 1. Although this validation process was quite subjective, the LAFS is, in fact, ideally suited to the study of ride qualities on large flexible airplanes when a large percentage of the energy at the crew station is concentrated in the relatively low-frequency structural modes.

Two significant aspects of the simulation were: 1) the simulated mission was accomplished in a heads-down environment with all visual information presented on displays in the cockpit. 2) The motion filter break points were established by having the pilots fly the most stringent terrain profiles and setting the filters to avoid "dumping" the simulator on its displacement stops.

The simulation was successful in that the pilot performed in different ride quality environments with statistically insignificant differences in performance, although significant preference was expressed for the low-gust-response environ-

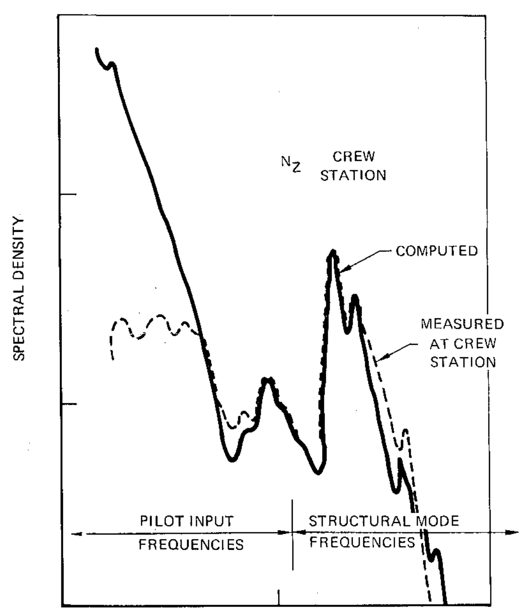

Fig. 11 Recovery of vertical power spectral density at crew station.

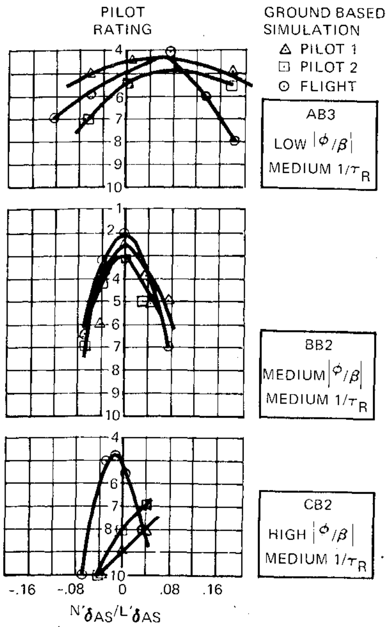

Fig. 12 Pilot rating.

ment. Improvement in restraint systems for both pilot and system operator, it was determined, would result in improved performance and environment acceptance.

Further, although the study was not an attempt to establish crew tolerance, it was determined that the vibration environment exceeded that described as intolerable by previous experimenters. There was not an indication of fatigue effects, either as a function of duration of the mission nor as a function of the ride quality of the vehicles.

VTOL Handling Qualities Criteria Study

The objective was to provide experimental data for establishing longitudinal and lateral directional handling qualities

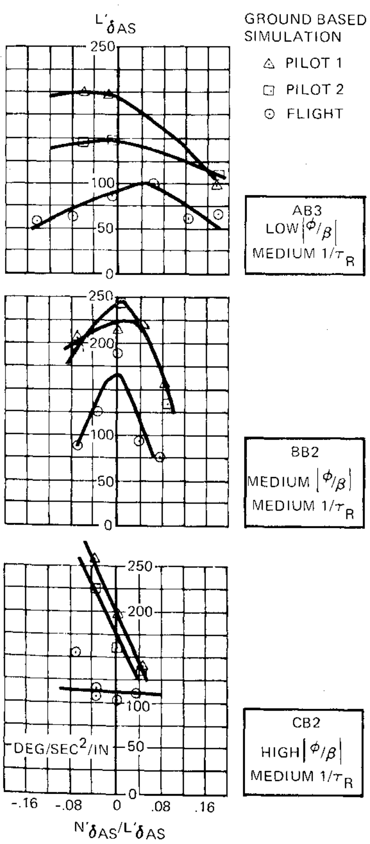

Fig. 13 Optimum aileron sensitivity.

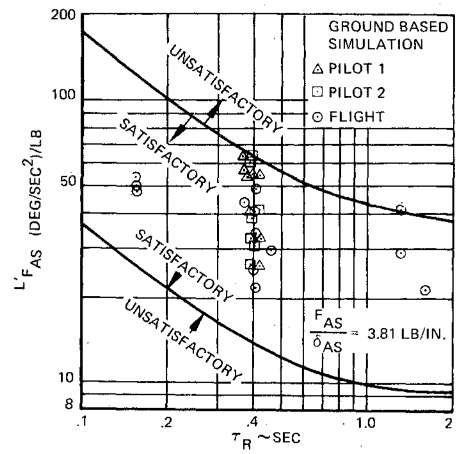

Fig. 14 Optimum aileron sensitivity.

specifications for vertical takeoff and landing (VTOL) aircraft in hover and low-speed maneuvering flight. The primary purpose of the initial experiments was to develop pilot rating data to help define the nature of an acceptable handling qualities boundary. The simulation was conducted on the RFS, and all six degrees of freedom of motion were simulated. The following tasks were performed: 1) vertical liftoff to hover at 30 ft, at the starting point on a ground-referenced square pattern, 2) trace out the square maintaining 30 ft altitude, 3) hover, making 90° turns, 4) perform cross-wind approaches at 30 ft followed by 90° turns, and 5) quick-stop maneuvers.

No attempt was made to validate quantitatively the simulation, but pilot comments indicated it was representative of VTOL airplanes they had previously flown. In a subjective manner, it appears that a simulation of the Visual Flight Rules low speed and hover maneuver of a VTOL aircraft can be accomplished with a high level of fidelity. Two significant aspects of the simulation were: 1) it was conducted in a heads-up environment with visual information portrayed on the cockpit instruments and on the spherical screen. 2) The simulator vision and motion break frequencies were obtained by comparison with flight test data, and pilot rating and observations from a previous program involving the NASA X-14A.

The simulation was successful in that the anticipated pilot rating boundary for acceptable handling qualities was essentially confirmed for airplanes with low drag factors. It was also established that the most significant parameters affecting pilot rating were the drag factors because of the large attitude changes that occurred when compensating for steady winds or when maneuvering.

Simulation Validation

To quantify the choice of washout characteristics and provide confidence in the drive technique, a series of experiments

Table 2 Evaluation configuration groups

	AB3 Low $\phi/\beta/_d$ med τ_R	BB2 Med $\phi/\beta/_d$ med τ_R	CB2 High $\phi/\beta/_d$ med τ_R	BA2 Med $\phi/\beta/_d$ sht τ_R	BC2 Med $\phi/\beta/_d$ long τ_R
ω_d	2.5	2.49	2.48	2.54	2.40
ζ_d	0.108	0.097	0.103	0.08	0.117
$\frac{\lvert\phi\rvert}{\lvert\beta\rvert}$	1.34	4.82	14	7.11	7
τ_R	0.4	0.37	0.46	0.156	1.3
τ_S	∞	987	111	91	−16.2
N_p'	−0.39	0.015	0.018	−0.025	0.044

Table 3 Comparison of pilot ratings and comments

Northrop case no.	Cornell code	Cornell pilot rating	Cornell pilot comment	Northrop pilot rating	Northrop pilot comment
Low ϕ/β Medium $1/\tau R$					
2	AB3/−0.06	6	Large adverse yaw generated during any maneuver	6	Very large adverse yaw due to aileron inputs
6	AB3/0	5.5	Coordination difficult at high roll rates uncomfortable response	5	The rudder coordination required is very tricky
10	AB3/0.18	8	For large inputs coordination is almost lost	5.5	The coordination technique deteriorates in effectiveness at large control rates
Med $\|\phi\|\beta\|$ Medium $1/\tau$R					
4	BB2/−0.06	6.5	Large adverse yaw and high $\|\phi/\beta\|$ make coordination and tracking difficult	6.5	Large adverse yaw causes difficulty in keep ball in center and coordination is difficult
14	BB2/0	2	Easy to coordinate good roll control	2.5	Easy to track and coordinate during maneuvers
18	BB2/0.07	7	Bank control difficult poor tracking due to dutch roll	6.5	Dutch roll makes bank angle tracking difficult
High $\|\phi\|\beta\|$ Medium $1/\tau$R					
9	CB2/−04	7	Large adverse yaw and $\|\phi\|\beta\|$ cause coordination problems	10	Horrendous adverse yaw due to aileron makes an impossible configuration to fly
3	CB2/0	5.5	Good roll performance but touchy in roll control	8.5	High $\|\phi/\beta\|$ in dutch roll make a real difficult configuration to fly
12	CB2/0.04	8	Almost always in a roll oscillation, poor bank angle control	7.5	Problems showing up mainly as roll oscillations

is being conducted. Initial results of a test in the LAFS are encouraging. (Future research will encompass the validation of the RFS.) A series of experiments had been conducted for the USAF by Cornell Aeronautical Laboratories on an inflight simulator version of the T-33 airplane.[3–5] At the present time, selected significant portions of the experiments on lateral directional handling qualities requirements for fiighters have been repeated on the LAFS.

The drive technique previously discussed has been employed. A sophisticated mathematical model of the Variable Stability T-33 has been mechanized and the cockpit instruments and force feel system have been accurately simulated on the LAFS. Table 2 shows the dynamic conditions that have been re-evalued on the ground based simulator.

One of the evaluation pilots had participated in variable-stability evalutions on the VSS T-33, although he had not flown the specific tests being re-evaluated on the simulator. The other pilot had no previous experience with the VSS T-33 but had numerous hours in the T-33 during a long flying career.

The tasks used in the evaluation were: 1) maneuvering the aircraft as desired to select optimum aileron gearing; 2) small maneuvers about level flight ($\phi = 10°$) with particular attention to the ability to maintain heading and make small heading changes; 3) precision maneuvering during 30° and 60° banked turns with particular attention to the ability to acquire and maintain precise bank angles and the ability to re-establish level flight on a desired heading; 4) rapid maneuvering with large bank angle changes with particular attention to the ability to acquire a given bank angle with changes of 30° to 120° and the ability to return to level flight; 5) bank angle command tracking task; 6) maneuvering the aircraft with disturbance inputs. One significant difference between the method of conducting the ground based evaluation and the flight evaluation was that, after accomplishing Task 1, Tasks 2–6 were performed at the control sensitivities used in the flight evaluation.

Comparison of the pilot ratings, Fig. 12, for three configuration groups shows good correlation between ground test and flight test results when the configurations are reasonably controllable, in the sense that the tasks can be performed.

More interesting than this is the similarity of pilot comment when choosing a pilot rating as shown in Table 3. Table 3 further indicates for the three configuration groups that pilot rating was selective in showing trends with variation in $|\phi/\beta|$ ratio and $N'\delta_A/L'\delta_A$ ratio. This would indicate that the proper interrelationships between attitude and translational cues are being obtained in the simulation. Even for cases when the pilot rating in flight differed by more than one rating point from that in simulated flight, the basis for the pilot rating as identified through pilot comment was similar in both cases.

Comparison of optimum sensitivity in Fig. 13 between ground test and flight test shows much larger sensitivities being chosen in ground simulation than in flight. It is thought this is due to a lesser inhibition to employ large roll rates on the simulator than in flight, but investigations are continuing to establish why the discrepancy occurs. It is important to notice in Fig. 14 that the sensitivities chosen in the ground tests, although high, remain within the acceptable boundaries established in previous Cornell flight tests.

Future experiments planned for the validation of the LAFS will not only investigate the choice of high control sensitivity, but will establish the need and usefulness of attitude washout, the possible elimination of translation acceleration motion cues, and the possible elimination of all translational motion-cues where the tasks being investigated allow it. It is anticipated that a catalog of washout characteristics can be established that is task related and validated by comparison with flight data.

Rationale for Choice of Simulators

There is doubt as to the practicality of any single simulator being capable of accurately simulating all the flight conditions that will be of interest in the system-oriented studies of the future. It appears that the RFS can be employed to study the conventional or vertical landing of fighter airplanes. The visual cues appear to be most important here, and the De-Florez type of display gives a very authentic reproduction of the real world. It seems possible that larger attitude capability can be provided than at present and the distortion associated with slaving the translational visual and motion system may be less significant than was first thought.

For formation flying studies it is probable the LAFS will be adequate. The motion cueing is within the capability of the existing motion system and the visual display is adequate.

Studies associated with high-speed interception will probably require the type of simulator referred to as the Differential Maneuvering Simulator. Accepting the fact that sustained load factor is not available, a high-quality reproduction of visual information with unlimited field of view seems necessary. The simulator provides this through the use of sophisticated servo driven optical equipment.

This optical manuevering type of simulator seems necessary for studies associated with close air-to-air combat. High-fidelity visual information on the target must be provided with a 360° field of view. It is doubtful that such visual fidelity could be provided in conjunction with a motion system capable of sustaining load factor.

For low-altitude, high-speed flight studies the LAFS has proved adequate. The motion system is capable of providing the motion cues authentically; and although previous simulations have been conducted with in-cockpit displays, a projected terrain-following display system should make VFR simulation possible.

The LAFS has been used in dive bombing investigations. It appears that some improvement in fidelity can be achieved by employing a visual display that allows better perspective simulation. Otherwise, the simulator provides an excellent mechanism for studying dive bombing. It is probable that the simulator with the proposed display can be used in studies associated with air-to-air combat. It would be necessary in this application to develop some logic to drive the target airplane, but this is well within the state-of-the-art.

It is anticipated that by minor refinements of the drive philosophy discussed in the previous sections and rigorous definition of the dynamic characteristics of the washout devices, these simulators will be extremely useful handling qualities research devices.

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Composite Airframe Design

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Manufacturing methods utilizing unidirectional glass reinforcement were applied to design and fabrication of a demonstration wing section representing the T2B airplane wing from station 115 to tip station 207.5. Design was substantiated by detail tests. Fabrication problems and solutions are discussed. Ultimate strengths of full-scale structures were 6% and 30% over the design goal with 40% less weight, 20% less estimated fabrication cost, greater bending stiffness-to-weight ratio, and greater torsional stiffness-to-weight ratio than an aluminum wing.

Introduction

THIS paper discusses the application of unidirectional, S-glass composite to a wing structure using available filament winding fabrication methods. Unidirectional, S-glass laminate has a substantially higher strength-weight ratio, for both tension and compression loads, than either glass fabric laminate or any aluminum alloy. Therefore, unidirectional S-glass roving is a candidate material for strength critical aircraft structures. The filament winding operation provides precise roving placement by machine and utilizes glass filament in an economical form. In addition, the manufacturing methods developed for unidirectional, S-glass aircraft structures will be applicable in principle to applying high modulus fibers to stiffness-critical aircraft structures.

Design Considerations

The demonstration article for this program represents the T2B aircraft wing outboard of wing station 115 as shown in

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Index categories: Aircraft Structural Materials; Structural Composite Materials; Optimal Structural Design.

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