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INITIAL OPERATING EXPERIENCE WITH AN AIRCRAFT SIMULATOR HAVING EXTENSIVE LATERAL MOTION

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Abstract

Late in 1969, a new research flight simulation facility, termed the Flight Simulator for Advanced Aircraft, was put into operation at Ames Research Center. This facility features an extensive cockpit motion system, emphasizing lateral motion for the simulation of lateral-directional control tasks. This paper describes briefly the motion capabilities of the simulator, and describes in detail the logic with which the motion drives are controlled to provide the most effective approximations of the motions of flight. Preliminary assessments of the effectiveness of these motions, in the simulation of large transport aircraft, are discussed.

INITIAL OPERATING EXPERIENCE WITH AN AIRCRAFT SIMULATOR HAVING EXTENSIVE LATERAL MOTION

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INTRODUCTION

The Flight Simulator for Advanced Aircraft, FSAA, was designed to provide uniquely extensive cockpit motion capabilities to aid in the study of handling qualities of large aircraft. This facility is described in detail in references 1 and 2. To quickly realize effective utilization of its six-degrees-of-freedom motion capability, it was necessary to design a motion constraint logic, or "wash-out" system, which was acceptable to the pilots involved in the first FSAA research program. Because experience with motion simulators combining rotational and linear modes is limited, and not directly applicable to the FSAA, tests were conducted to empirically determine a satisfactory motion logic.

The resulting FSAA wash-out system utilizes the commonly-used technique of applying linear high-pass filtering to the computed airplane motions, so that no sustained velocities are asked of the simulator. The selected characteristics of these filters reflect the nature of the simulated flight tasks and the excursion capabilities of the motion drives. They also reflect additional considerations which arise from the combining of rotational and linear drive modes, considerations that define requirements for coordination of drive signals, and present opportunities to utilize angular displacement (tilt) to sustain the sensed linear accelerations. In addition to the linear filter "wash-out," the motion constraint logic employs nonlinear excursion limiting logic ("soft limits").

This paper briefly describes the mechanical characteristics of the FSAA motion system and the flight tasks simulated in the initial research program. The selected motion constraint logic is described in detail, and the effectiveness of the simulator motion in the initial program is discussed. Also presented are observations derived from very brief exploratory experiments aimed at obtaining generalized definitions of motion requirements for flight simulators. These tests examined the effects of constraining motions to considerably smaller excursions than obtainable with the FSAA by increasing wash-out filter frequencies, and by simple attenuation of acceleration signals.

NOTATION

a_y acceleration sensed in airplane cockpit, parallel to lateral axis, ft per sec^2

a_{y_s} acceleration measured in simulator cockpit, parallel to lateral axis, ft per sec^2

$\dot{p}$ angular acceleration of aircraft about its longitudinal axis, rad per sec^2

$\dot{q}$ angular acceleration of aircraft about its lateral axis, rad per sec^2

$\dot{r}$ angular acceleration of aircraft about its vertical axis, rad per sec^2

$\ddot{X}$ longitudinal acceleration command, prior to wash-out filter, derived from airplane body-axes longitudinal acceleration, ft per sec^2

$\ddot{Y}$ lateral acceleration command, prior to wash-out filter, derived from airplane body-axes lateral acceleration, ft per sec^2

$\ddot{Z}$ vertical acceleration command, prior to wash-out filter, derived from airplane body axes vertical acceleration, ft per sec^2

θ airplane pitch attitude, rad.

ϕ airplane angle of bank, rad.

ϕ_s angle of bank of simulator cockpit, rad

ψ_s angle of yaw of simulator cockpit, rad

X_s longitudinal displacement of simulator cockpit, ft.

Y_s lateral displacement of simulator cockpit, ft.

Z_s vertical displacement of simulator cockpit, ft

$\left.\begin{array}{l}\Sigma F_x \\ \Sigma F_y \\ \Sigma F_z\end{array}\right\}$ body-axes aerodynamic and reaction forces on the airplane, lb

m airplane mass, slugs

ℓ distance from vertical axis of airplane to the cockpit, ft

z distance from longitudinal axis of airplane to the cockpit, ft

s Laplace operator

ω forcing frequency, rad/sec

ζ damping ratio

D_x transfer function denominator $(s^2 + 2\zeta\omega_x s + \omega_x^2)$

g acceleration due to gravity, 32.2 ft/sec^2

τ time constant of first order filter, sec

$\left.\begin{array}{l}\omega_\theta \\ \omega_\phi \\ \omega_\psi \\ \omega_x \\ \omega_y \\ \omega_z\end{array}\right\}$ designate natural frequencies of corresponding wash-out filters

FSAA MOTION SYSTEM

Design considerations. The specifications for the FSAA motion system reflected a growing concern regarding the large and complex lateral motions of the cockpit which accompany the lateral-directional maneuvering of very large aircraft. Fixed or limited-motion simulators have not been impressive in attempts to simulate tasks in which directional control (with rudder) is of major significance, and it was reasoned that the provision of accurate lateral acceleration cues was necessary. A usable travel of ±40 ft was chosen for the lateral motion of the FSAA. Mechanically, this became the initial mode relative to the inertial (earth) reference. The vertical and longitudinal motions are relatively restricted, being ±4 ft and ±3.5 ft respectively. Practical structural considerations influenced the vertical travel limits, but experience with several vertical motion devices at Ames had indicated that ±4 ft would provide important higher-frequency vertical acceleration cues, including those associated with turbulence, airframe buffet, and ground contact. Provisions for longitudinal motion were in large part speculative.

The angular drives, in order away from the inertial reference, yaw, pitch, and roll, were designed in accordance with previous experience at Ames, and incorporate angular excursion capability in excess of that required for large aircraft simulation.

Motion system performance. All modes of motion are electrically driven. Mechanical buffers are provided as the ultimate motion limiters; however, an array of electrical limiters function to constrain position, velocity, and acceleration. Violation of any of these limits interrupts the operation of the motion system until a reset procedure is conducted. When the motion system is operating in a simulation mode, it responds to rate command signals derived from the simulation computer, and position feedbacks are provided to the computer for use in the motion constraint logic. The performance characteristics of the machine, as it was operated in its initial program, are listed below:

MODE	TRAVEL	ACCELERATION	FREQ. AT PHASE LAG = 30°
Lateral	±40 ft	12 ft/sec^2	1.0 Hz
Vertical	±4.0 ft	12 ft/sec^2	2.2 Hz
Longitudinal	±3.5 ft	9 ft/sec^2	1.8 Hz
Yaw	±24°	1.6 rad/sec^2	1.7 Hz
Pitch	±15°	2.4 rad/sec^2	2.0 Hz
Roll	±36°	3.2 rad/sec^2	3.0 Hz

DERIVATION OF DRIVE SIGNALS

Accelerations

A rigorous development of acceleration signals for driving the motion system would include the resolution of body-axis cockpit accelerations of the simulated airplane into the inertial axes system of the machinery through the resultant orientation of the rotational drives.* However, for this initial operation of the FSAA, in the interest of simplicity and flexibility, airplane-axis accelerations were used without resolution. This was felt to be justified in view of the small and transient nature of attitude excursions of the simulator cockpit. The basic drive signals for the angular drives were the body axes angular accelerations $\dot{p}$, $\dot{q}$, and $\dot{r}$. The linear drives required more complex commands which reflect the 1g static environment of the simulator. The vertical drive acceleration signal was derived from summed aerodynamic and inertial forces:

$$\ddot{Z} = (\Sigma F_z/m) \cos \phi + \ell\dot{q} - g$$

The cos ϕ term is included to eliminate the vertical acceleration bias of steady-state level turning flight. The lateral drive signal was composed of two elements:

$$\ddot{Y}_1 = (\Sigma F_y/m) + \ell\dot{r} + z\dot{p} = a_y$$

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* Such a rigorous development, applied to a motion constraint system similar in principal to that discussed in this paper, is presented in reference 3.

which describes the lateral acceleration that would be observed in the airplane cockpit, and a component, $\ddot{Y}_2$, a function of simulator cab bank angle, which maintains proper orientation of the total acceleration vector. The longitudinal drive signal is described similarly, as:

$$\ddot{X} = (\Sigma F_x/m) - z\dot{q} - |\ell r^2| - |\ell q^2|$$

Motion Constraint Logic

It was the basic premise behind the development of the motion constraint logic that no acceleration sensed by the simulator pilots should be contaminated by unprogrammed components resulting from motions of other drive modes. Thus, coordination of the roll and lateral modes was required in order to provide a lateral acceleration, a_{y_s}, that was modified only by "wash-out" high-pass filtering. However, even this basic premise was violated for the purpose of reproducing low frequency components of a_y. As will be discussed later, false roll inputs were used to provide "tilting" of the simulator cockpit for simulation of low frequency or sustained lateral acceleration.

High-pass filtering of acceleration signals: Commonly, first-order high-pass filters have sufficiently constrained rotational modes of motion simulators, since the rotational accelerations of aircraft are rarely sustained. Since linear accelerations of aircraft are often sustained, it is necessary to use at least a second order filter to define a low frequency acceleration-excursion relationship. In an all-axis system such as the FSAA, it becomes desirable to carry the second-order filter over to the rotational modes.

Each of the active motion drives of the FSAA was provided with a filter circuit of the following description:

$$\frac{\ddot{X}_s}{\ddot{X}} = \frac{s^2}{s^2 + 2\zeta\omega_x s + \omega_x^2} = \frac{s^2}{D_x}$$

or in terms of resulting displacement:

$$X_s = \frac{\ddot{X}}{D_x}$$

This circuit is diagrammed in figure 1(a), and the associated dynamic response is described in figure 1(b).

To provide the necessary coordination between the lateral-directional modes, ω_ϕ and ω_ψ were made equal to ω_y, which was defined by the maximum excursions of ϕ required in the simulated flying task. Of course, all damping ratios were the same.

Coordination of lateral-drive acceleration with simulator angle of bank. - As mentioned previously, the total acceleration drive signal, $\ddot{Y}$, contained a component $\ddot{Y}_2$ proportional to ϕ_s. Because of the physical nature of the filter and drive circuitry, the derivation of $\ddot{Y}_2$ included some approximations. To keep proper orientation of the total acceleration vector relative to the cockpit as it is rolled, a lateral drive system acceleration equal to g tan ϕ_s is required. However, due to the wash-out circuitry, it is not possible to command lateral acceleration directly with the position signal, ϕ_s, so the following procedure was employed:

Without a Y_2 term, the sensed error in cockpit lateral acceleration is

$$\Delta a_{y_s} = -g \sin \phi_s = -g \sin \frac{\dot{p}}{D_\phi}$$

The correction term used was

$$\ddot{Y}_2 = g\phi$$

thus

$$\Delta \ddot{Y}_s = \frac{\ddot{Y}_2 s^2}{D_y}$$

or

$$\Delta \ddot{Y}_s = g\phi \frac{s^2}{D_y} = g\phi_s$$

therefore, $\Delta \ddot{Y}_s$ is equal to $- \Delta a_{y_s}$, assuming

(a) $\phi = \frac{\dot{p}}{s^2}$

(b) $\phi_s = \sin \phi_s = \tan \phi_s$

(c) $\omega_y = \omega_\phi$, $(D_y = D_\phi)$

The time history shown in figure 2 illustrates the response of the simulator lateral modes to a rolling maneuver of the simulated airplane. (For this case, a_y has been held to zero).

Similar logic has not yet been applied to the combination of pitch and longitudinal drives. Due to the relatively limited longitudinal travel, compensation can be provided for only small high-frequency pitch excursions of the simulator cockpit.

Simulation of steady-state accelerations. The lower frequency portions of the lateral and longitudinal acceleration spectrums, which are removed by filtering of the linear motion drive signals, can be provided by tilting the cockpit in roll and pitch respectively.

The following "tilt" logic was developed for the FSAA lateral drive modes:

Since

$$\frac{\ddot{Y}_s}{\ddot{Y}_1} = \frac{\ddot{Y}_s}{a_y} = \frac{s^2}{D_y}$$

it is necessary to tilt the cab in roll to provide the residual:

$$\frac{g\Delta\phi_s}{a_y} = -\frac{(D_y - s^2)}{D_y}$$

Again we are assuming $\phi_s = \sin\phi_s$ and setting $\omega_\phi = \omega_y$:

$$\Delta\phi_s = -\frac{a_y}{g} \frac{(2\zeta\omega_\phi s + \omega_\phi^2)}{D_\phi}$$

It can be seen that a step input of a_y calls for a step in simulator rolling velocity, or infinite rolling acceleration. Because of the distance of the cockpit from the yaw axis, cockpit lateral accelerations in large aircraft can have significant high-frequency content (rudder kicks, gusts, outboard engine thrust variation). Therefore, it is desirable to filter the a_y input to the roll drive with a first order filter of the form

$$\frac{1/\tau}{s + 1/\tau}$$

in order to reduce the peak roll accelerations.

In figure 3 are shown the responses of the lateral and roll modes to a step of a_y. Cases with and without the filter on the input to the roll drive are illustrated. The roll accelerations shown in figures 3(b) and 3(c) assume a motion system servo response characterized by a first-order lag of 0.1 seconds.

Similar logic was used to pitch the cockpit to provide sustained longitudinal acceleration; however, due to the limited longitudinal travel, overall fidelity of longitudinal acceleration presented to the simulator pilot was less than that demonstrated for lateral accelerations. In order to minimize the effects of anomalous pitch accelerations, the longitudinal acceleration signal to the pitch drive was subjected to a filter of the form

$$\frac{1}{(S+1)^2}$$

Motion limiting. In order to utilize all of the motion system capability it is desirable to establish wash-out and attenuation configurations that will result in occasionally reaching the excursion limits during the maneuvers required in the simulation studies; but to permit these limiting excursions to interrupt operations is intolerable. Therefore, a limiting logic was incorporated in the wash-out filter circuitry that in normal operation eliminates the possibility of actuating the servo-system or mechanical limiters that do interrupt the operation.

A schematic of the limit logic is shown in the figure 4(a). The acceleration limit on amplifier No. 1 prevents an overcurrent cut-out of the drive motor. The velocity drive signal integrator, No. 2, is subject to a variable limit that is a function of the position feed-back signal from the drive system. This relationship is described in figure 4(b). The velocity-position relationships at Points A and B are defined to (1) limit maximum steady-state velocity, and (2) limit maximum decelerations to values equal to or less than the limit on amplifier No. 1. Arrestments from steady-state commanded velocities are characterized by a step deceleration, proportional to the original velocity, which decays exponentially as the drive approaches the established position limit.

OBSERVATIONS AND DISCUSSION

Basic Wash-out Configuration

As indicated in the introduction, the opportunities to examine a range of motion variables prior to research use of the FSAA were limited. As a consequence, the great majority of experience with the motion logic described in this paper was obtained with constants that were empirically determined as suitable for the conditions of the initial program, which involved the simulation of large transport aircraft in the low-speed flight regime. Five research pilots participated in the study, which emphasized the take-off and initial climb maneuver, but also included maneuvers used in basic handling-qualities assessment. These "typical" airplanes were simulated.

(1) A DC-8 type representative of current jet transport

(2) An enlarged "DC-8" intended to represent the 600,000 pound category of subsonic transport

(3) A "Concorde-like" supersonic transport

Essentially all of the 60 hours of "flying" was performed in the "VFR" environment. that is, utilizing a closed-circuit TV visual simulation system (Ames-Redifon). For the majority of the research program, the following motion logic was used:

(a) $\omega_Y = \omega_\phi = \omega_\psi = 0.5$ rad per sec

$\omega_\theta = \omega_Z = \omega_X = 1.4$ rad per sec

$\zeta = 0.7$

(b) $\dot{p}$ and $\ddot{Y}_2$ attenuated to 50% of their computed values

(c) $\Delta\phi_S$, tilt for low frequency a_{y_s} incorporated with $\tau = 0.5$ seconds

These constants reflect the following considerations:

1. Accommodations of steady-state values of ϕ up to 36°. The value of ω_ϕ, and the attenuation of $\dot{p}$ and $\ddot{Y}_2$ combine to define the maximum steady-state value of ϕ accommodated by the lateral travel of the simulator.

2. Accommodation of sustained incremental airplane vertical acceleration of ± 8 ft/sec^2.

3. Optimization of a_y reproduction for simulation of outboard engine failures during take-off.

<u>Pilots' reactions to simulator motions</u>: All of the subject pilots were appreciative of the motion cues supplied by the FSAA using this motion logic. Most noted, of course, was the high fidelity reproduction of cockpit lateral

acceleration, which they had not experienced previously in simulations. In their opinion, this greatly increased the effectiveness of the simulator in the evaluation of lateral-directional handling qualities. They agreed that the task of coping with a simulated outboard engine failure on take-off closely approximated that experienced during actual flight drills. Comparison maneuvers, conducted with no simulator motion, demonstrated a reduction in the capability of the pilot to stabilize the simulated aircraft. Apart from the measureable effects on particular task performance, it was evident that the reproduction of a_y was extraordinarily effective in creating the general impression of "realism". This increase in simulation fidelity was especially noted by the two pilots that had little experience with visual simulations; they observed that the motion cues apparently increased their acceptance of the visual dynamic information in the landing approach maneuver, since they experienced few of the runway alignment problems that they had encountered with previous visual landing simulations.

The attenuation of the roll modes, and the spurious roll inputs accompanying the tilt mode of the cab used to provide low-frequency lateral accelerations, evoked no spontaneous comments from the pilots. When informed of these characteristics, the pilots agreed that within the scope of flight tasks in the initial program, such accommodations were quite acceptable.

It is appropriate to note here that control of the lateral acceleration of the airplane cockpit is especially amenable to accurate simulation. In conventional aircraft, the maximum values of lateral acceleration are small, and the control task is predominantly one of stabilizing and nulling the acceleration sensed in the cockpit. Moreover, magnitudes of acceleration, and the nature of the yaw control loop do not vary greatly with the flight task being simulated.

The vertical acceleration cues were regarded as helpful, particularly in the take-off rotation. Though the filtering distortions of the wash-out were obvious, there was no clear evidence that the phase shifts near the wash-out natural frequency had destabilizing effects on longitudinal control. Reproduction of the accelerations produced by ground contact or airframe buffet was an obvious contribution to simulator realism.

In summary, the initial pilot response was very encouraging, especially since the motion system was not completely flawless in its operation. Potentially most disturbing was velocity-related audible noise in the lateral drive, and to a lesser extent, in the vertical drive. Even though the noise was masked somewhat by deliberate amplification of the engine noise simulation, its tolerance by the pilots was a measure of their appreciation of the positive contributions of the motion.

Variations in Motion Logic

In the course of the development of the simulator, it was possible to examine briefly variations in some of the motion logic describing parameters. The objectives were: (1) to determine the sensitivity of the pilot to individual motion constraint factors; and (2) to gain some general knowledge regarding the relationship between linear motion capabilities and simulator effectiveness. These changes were made primarily in the lateral-directional modes, and were only subjectively evaluated on the basis of brief individual experience. This latter qualification may help explain the vague nature of many of the observations which follow. It also must be remembered that all observations were made in the context of the dynamic characteristics of a large subsonic jet transport flying at low speeds. Thus the levels of acceleration in all modes were low, and no high-frequency lightly damped dynamic modes were present.

Natural frequency of wash-out filters: The effects of changes in the wash-out filter natural frequencies are of paramount interest because maximum acceptable values of natural frequency, together with acceleration attenuation factors, define minimum motion travel requirements. The FSAA motion system was operated with lateral-directional filter frequencies of 0.35, 0.5, 0.7, 1.0 and 1.4 rad/sec. With no attenuation in the roll mode, the lower frequencies corresponded to maximum airplane bank angles of 9, 18, and 36 degrees. For the flight tasks being simulated, ± 18 degrees of roll freedom were considered the minimum acceptable, thus $\omega_\phi = 0.35$ was considered unsatisfactory although no disturbing dynamic effects of the wash-out filter was noted. With $\omega_\phi = 0.5$, the first slight subjective evidence of contradiction between visual and motion cues was noted. This was evident during excitation of the Dutch-roll mode, which for the simulated airplane was poorly damped and had a natural frequency of about

0.85 rad/sec. At this ratio of $\dot{\omega}/\omega_\phi$, the phase lead attributable to the filter is about 50 degrees. Increasing ω_ϕ produced stronger sensations of confusion in the dutch-roll maneuver, and at values of 1.0 and 1.4, the wash-out filtering appeared to significantly interfere with the pilot's ability to stabilize this mode. This is understandable since the phase lead becomes greater than 90 degrees, and only modest filtering attenuation occurs. This experience illustrates the importance of considering the airplane's dynamic characteristics, as well as any predominate maneuvering frequencies related to the flight task, when wash-out filters are chosen. In these tests, the disturbance due to phasing was limited to the roll mode because there was very little cockpit lateral acceleration, a_y. associated with the dutch-roll; thus, in total, the simulator motions were positive in their contribution even to the highest values of ω_ϕ.

Varying the filter frequency of the vertical motion mode from 1.0 to 2.0 rad/sec produced no striking changes in subjective evaluation. The lower values of ω_z were recognized as being most effective, but with the highly damped longitudinal response of the simulated airplane, the frequency sensitivity problem seen in the roll mode did not appear in the vertical mode. The lack of low-frequency vertical acceleration components was, of course, obvious; and the pilot tended to consider the simulator vertical motion as a partial substitute for, rather than an approximation of, the real thing. At $\omega_z = 1.0$, the limiting low-frequency maneuvering accelerations are ± 4 ft/sec^2 (0.124g), a value which is acceptable in only a limited number of flight tasks. In the landing approach maneuver, this filter was only marginally acceptable, because the non-linear motion constraints were encountered often enough to produce an inhibiting influence on the pilot's control procedures.

Attenuation of roll acceleration: Direct acceleration attenuation has been recognized as a rational adjunct to linear filtering for motion constraint. In the FSAA tests, it was used only in the roll mode. As noted previously, the initial research program utilized as attenuation of 0.5 in roll input, p. This value was chosen after brief comparative evaluations at conditions of no attenuation, 0.5 attenuation, and complete elimination of the roll acceleration input. These conditions were evaluated with and without simulated turbulence containing strong roll disturbances.

In the absence of simulated turbulence, attenuation of the roll mode was judged beneficial. An attenuation of 0.5 reduced the phase-related disturbances noted at $\omega_\phi = 0.5$ and above, and excursions and velocities of the lateral drive system were halved, significantly reducing the motion system noise. The two pilots that operated the simulator with no roll mode at all stated that they did not miss it. However, these factors must be noted in qualification of these opinions: (1) normal maneuvering roll accelerations for the simulated aircraft were very low (less than 0.2 rad/sec^2), (2) both pilots were well practiced with the visual simulation system in fixed cockpit simulators, and (3) the cockpit lateral accelerations accompanying roll control inputs were accurately represented. With simulated turbulence, attenuation of the roll mode by 50% was immediately obvious to the pilots, and was interpreted as a reduction in turbulence severity. This experience indicates that if a demanding turbulence environment is to be an important part of a motion simulation, the higher frequency accelerations should not be severely attenuated.

Auxiliary roll mode for simulation of low-frequency lateral acceleration: This mode was evaluated for the range of ω_ϕ mentioned previously, but without the Y_1 input filter. The false roll accelerations were tolerated to a $\omega_\phi = .7$, but above that value, the roll anomaly inspired obvious countering control inputs. At $\omega_\phi = 1.4$, the roll acceleration was strong enough to consistently inspire the wrong rudder input when the pilot attempted to counter the yawing acceleration produced by a simulated engine failure. Further experience is needed to determine if, as is probable, filtering would render this concept useful at the higher values of ω_ϕ.

The preliminary conclusion drawn from the experience with this cockpit "tilt" mode is that it did not constitute a vital part of the total motion simulation. At the lower values of ω_ϕ, where anomalous roll acceleration was no problem, the pilots had difficulty sensing, in dynamic maneuvers, whether or not the mode was activated, though simulated steady side-slip could immediately define its presence.

CONCLUDING REMARKS

The most obvious conclusion to be drawn from the experience to date with the motion capabilities of the FSAA is that reproduction of cockpit lateral acceleration is extremely effective in increasing the overall subjective fidelity of an aircraft simulation. For large aircraft, due to size and to the basic nature of their maneuvering dynamics, the cockpit lateral acceleration cues appear to be much more important than roll acceleration cues. There was the indication that this observation might be extended to the generalization that in each plane of motion the linear cues are much more valuable than the rotational cues. Assuming that this is the case, and that appropriate direct attenuation of acceleration inputs is exercised, very effective simulations of large transport airplanes should be realizable with motion systems having considerably smaller lateral excursions than that of the FSAA. These observations, of course, lead to the recommendation that unique capabilities of the FSAA be utilized to gather definitive experimental data for use in the design of both training and research flight simulators.

A secondary observation lends support to the hypothesis that lack of motion cues has a strong adverse effect on the effectiveness of visual simulation and that some subjective shortcomings of simulations of visual flight tasks are attributed to image deficiencies rather than to their real source, which is lack of motion cues. Further experiments to define the relative importance of motion and visual fidelity to the effectiveness of visual simulation are recommended.

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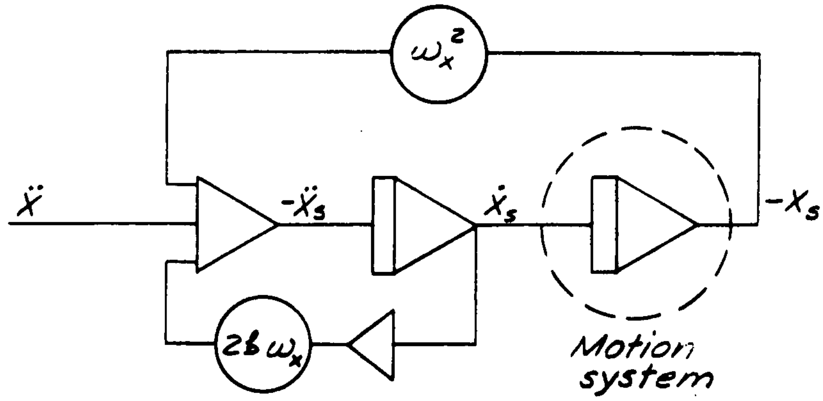
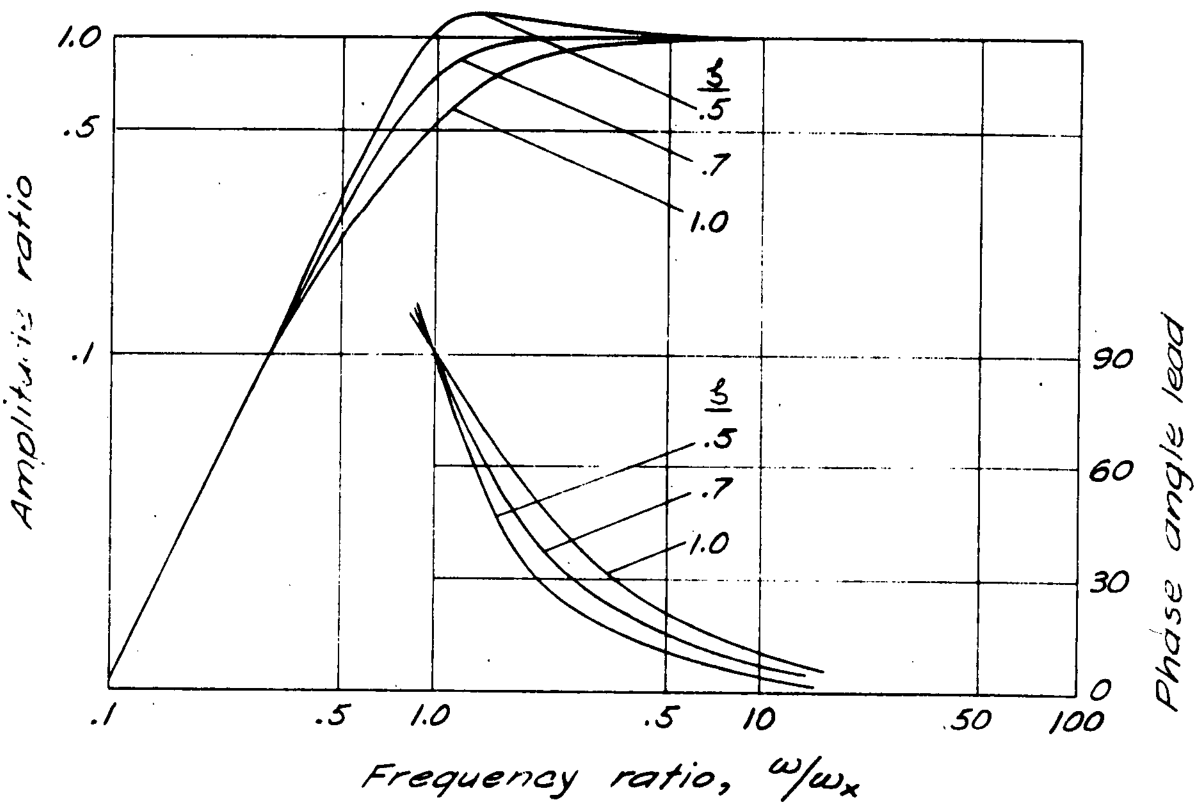


(a) Wash-out system schematic.



(b) Dynamic response of wash-out system.

Figure 1.— Basic second-order high-pass-filter motion constraint system used in the FSAA.

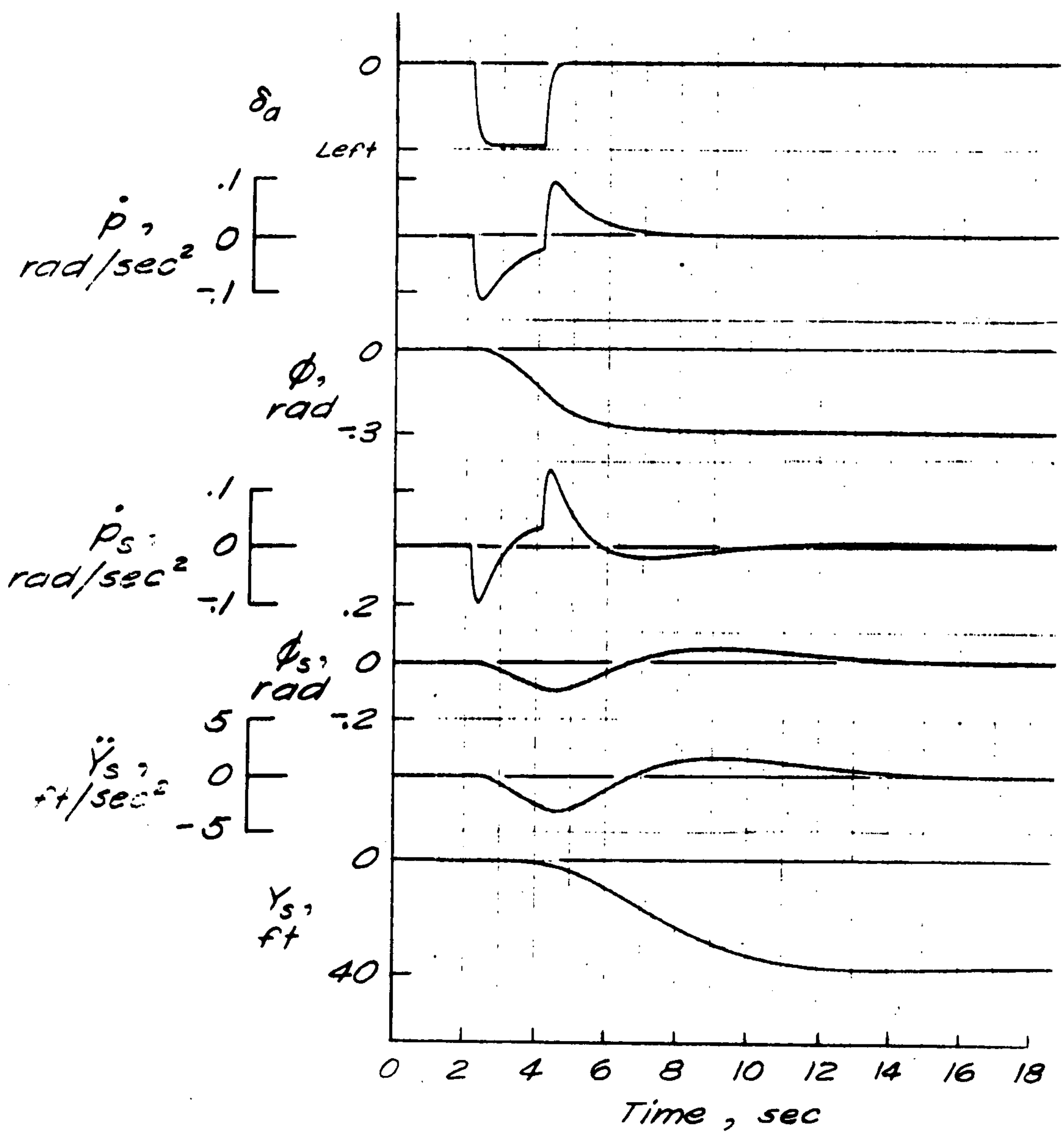


Figure 2.— Response of motion logic system to turn-entry maneuver, $\omega_\phi = \omega_Y = 0.5$, $\zeta = 0.7$.

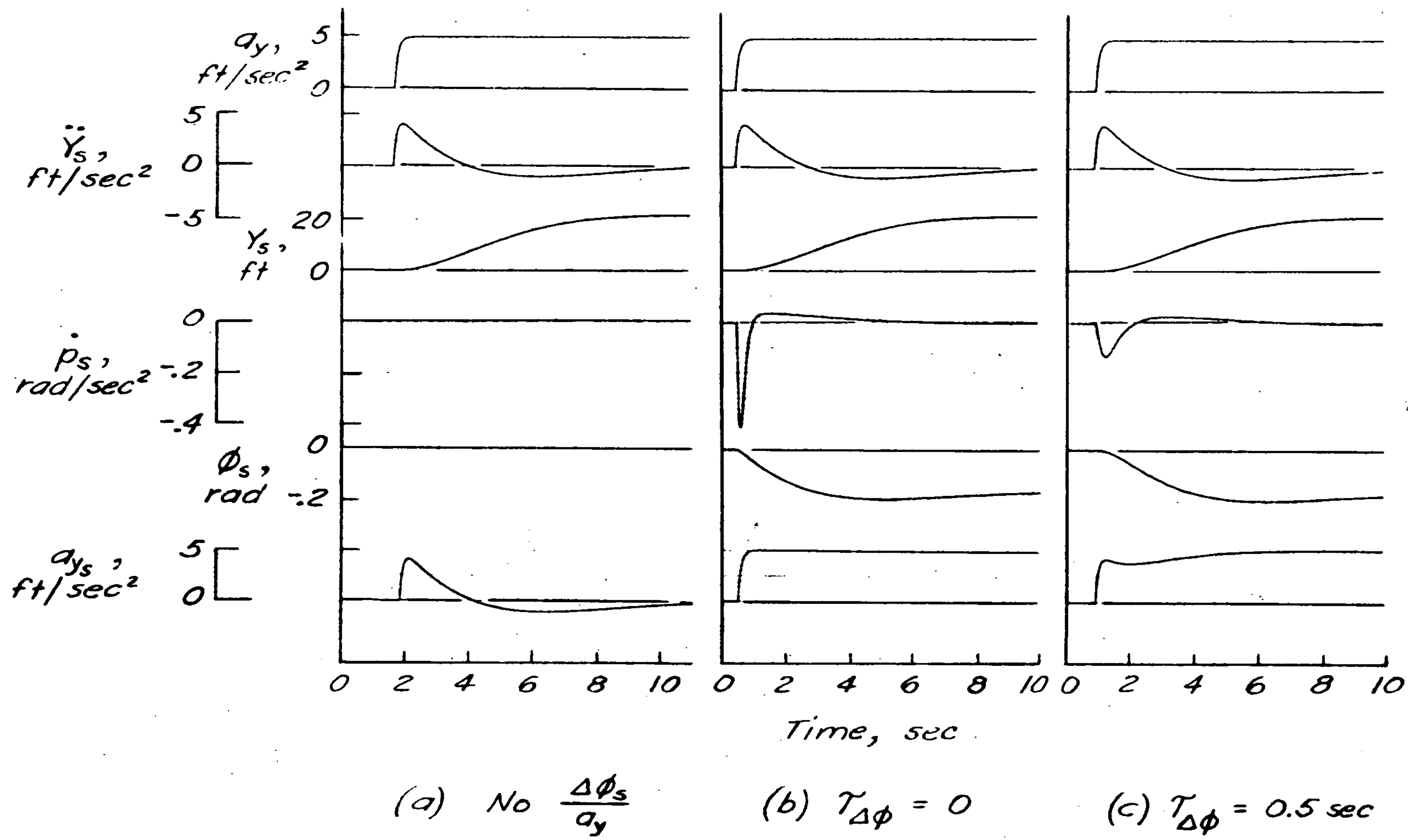
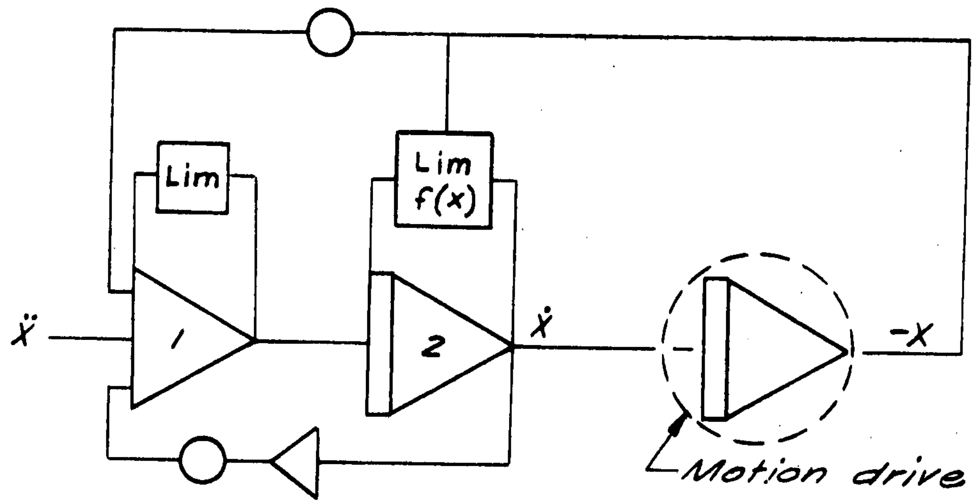
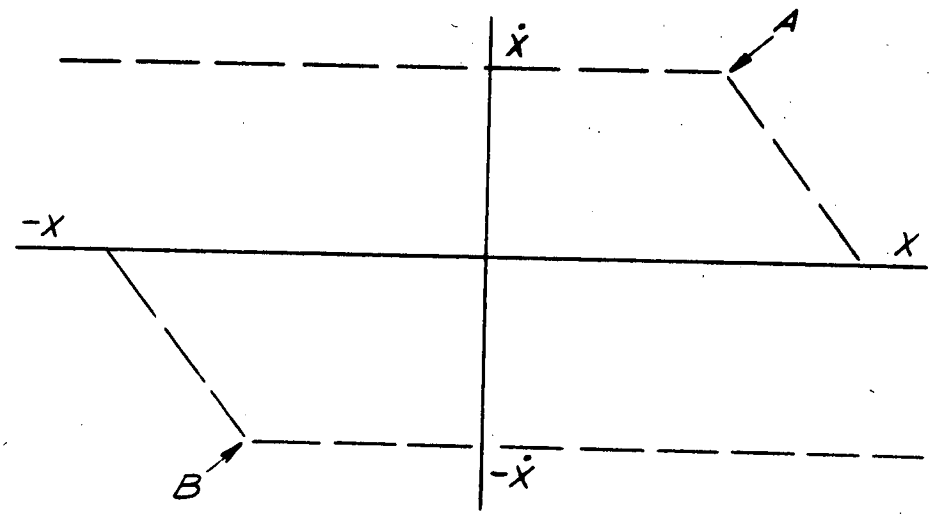


Figure 3.— Response of motion logic system to step of airplane cockpit lateral acceleration, a_y.



(a) Motion limiting circuit.



(b) Limiting envelope.

Figure 4.— Limiting logic in wash-out circuit.