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GENERAL REVIEW OF PILOTING PROBLEMS ENCOUNTERED DURING SIMULATION AND FLIGHTS OF THE X-15

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GENERAL REVIEW OF PILOTING PROBLEMS ENCOUNTERED DURING SIMULATION AND FLIGHTS OF THE X-15

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The advantages of simulation have been expounded for years by engineers and pilots. We cannot presently ignore or fail to take advantage of the prediction capability of simulation in the development of a new aircraft or flight vehicle. The question, however, is: How complete must the simulation be to anticipate the many possible problems that could be encountered?

This paper describes a few of the problems encountered on X-15 flights that were not anticipated during simulation. Many of these problems were consequences of simulation deficiencies resulting from the omission of complex and costly flight-environment conditions.

The X-15 flight experience covers a wide range of environmental conditions from high longitudinal-acceleration boost profiles to low lift-drag-ratio landings. This offers a unique opportunity to comment on a number of pertinent points regarding simulation and simulation requirements.

DESCRIPTION OF SIMULATORS

Figure 1 shows the hardware mockup of the X-15 cockpit and control system with simulated control surfaces. Actual electronic control components were used as simulator hardware. Some of the analog computing equipment and the plotter and recorders used in the simulation are also shown.

For the mechanization of the complete six-degree-of-freedom equations of motion, which represented the X-15 aerodynamics, analog computers were used. Nonlinear aerodynamic variables were programed as a function of Mach number and angle of attack.

The simulator was frequently updated in line with flight data and hardware modifications to insure accurate performance and controllability matching for subsequent flight simulations. The wind-tunnel derivatives, in general, proved to be fairly accurate, and few changes were required to improve the simulation of the actual vehicle. Such factors as motion, acceleration, and visual displays were omitted because of the added

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complexity, cost, and nonavailability of the necessary equipment. Other types of simulations, such as the F-104 and the centrifuge, were resorted to in an attempt to anticipate problems resulting from these omissions. But, there were still problems. This, of course, is one of the reasons for actual flight testing--to determine whether there are problems that have not been anticipated.

EFFECTS OF IMPROPER SIMULATION

For any type of simulation, it is logical to question how complete the simulation should be in terms of cockpit duplications, systems operation, and flight-environment effects. The X-15 experience shows that, at least for pilot training, the cockpit simulation must be as complete as possible.

Cockpit

Two examples of seemingly minor differences between the simulator and the airplane illustrate the importance of cockpit duplication. Consider, for example, an incident in which the polarity of the simulator switch that energizes the trim button was different from the switch in the airplane. The pilot practiced his flight plan in the simulator and became proficient; however, in the airplane the practiced technique was no longer useful. By the time he made the necessary correction, he was so far off the desired flight profile that, for research purposes, the flight was of limited usefulness.

On another occasion, an instrument was different in the airplane than in the simulator. The pilot checked the panel for the position of the needle rather than for the actual reading. This also resulted in the flight being off the desired plan. Both of these differences between simulator and airplane were readily apparent prior to flight; however, the consequences were not fully recognized until after the actual flight was made.

Systems

Failure to properly duplicate systems operation and the in-flight consequences are illustrated in the following example. The hydraulic output of the pumps used to supply the simulator control system did not match that of the airplane. During an in-flight maneuver, the pilot experienced a complete loss of artificial pitch and roll damping and an unstable control system because of control-system feedback characteristics (fig. 2). An investigation of the cause of the system instability indicated that the high gain capability of this adaptive system could not only saturate the control-surface rates, but the actuator servo rate as well. The pitch gain was at a maximum just prior to the maneuver. When the maneuver was initiated by the pilot with a relatively low-rate pitch and roll command, the system responded with a signal to the actuator servo that exceeded the rate capability. System damping of the airplane response began with the first motions and, since the gain was at a maximum, the damping signals were also asking for more servo actuator rate than could be supplied. Damping of these motions was achieved with a reduction in pitch gain, which the system eventually scheduled. This instability could not be duplicated in the simulator until the hydraulic-system output was increased to match that of the airplane.

Structural Environment

An omission in properly duplicating the flight-environment effects almost caused the loss of an airplane. During reentry from an early altitude-buildup flight, a severe vibration at 13 cps was experienced by the X-15 for approximately 1 minute. After the pilot lowered the stability-augmentation-system gain, and with an increase in dynamic pressure, the shaking stopped. The pilot landed without further incident. An investigation into the cause of the vibration (fig. 3) indicated that at low dynamic pressure in the absence of aerodynamic damping the lightly damped horizontal-tail structure was excited at its natural frequency by pilot control inputs. The X-15 inertial reaction to this oscillation was sensed by the stability-augmentation-system gyros which closed the loop through the control system. This problem could have been predicted on the fixed-base simulator if sufficient consideration had been given to the possibility of its occurrence in flight. The solution to the problem was developed on the simulator. A redesign of the augmentation-system filter was required to uncouple the system. The redesigned filter was checked out on the fixed-base simulator to insure proper attenuation at 13 cps. This change avoided the shaking problem.

Acceleration, Motion, and Visual Cues

Even if the cockpit and control systems are duplicated, the omission of other cues, such as acceleration, motion, and visual, can result in serious problems. Some examples are given in the following sections to illustrate the possible effects on a mission.

Acceleration.– Acceleration cues were considered an unnecessary luxury in the X-15 simulator. The original X-15 pilots were exposed to typical mission simulations on the U.S. Navy centrifuge at Johnsville, Pa., but not for training simulation purposes. These tests were primarily to determine the detrimental effects of acceleration on controllability during typical speed and altitude missions.

Later X-15 pilots had participated in various centrifuge programs but had not been subjected to X-15 mission accelerations during the training period.

The lack of acceleration capability in the X-15 simulator has not resulted in any serious problems during the flight program. There have been surprises, though, which have had some subtle effects on pilot impressions as a result of this omission.

A typical altitude mission is shown in figure 4. Normal and longitudinal accelerations, a_z and a_x, are shown in the lower plot. Prior to my first flight, my practice simulation had been done in a relaxed, head-forward position. The longitudinal acceleration at engine light forced my head back into the headrest and prevented even helmet rotation. The instrument-scan procedure, due to this head position and a slight tunnel-vision effect, was quite different than anticipated and practiced. The acceleration buildup during engine burn (4g max) is uncomfortable enough to convince you to shut the engine down as planned. This is the first airplane I've flown that I've been happy to shut down.

Engine shutdown does not always relieve the situation, though, since, in most cases, the deceleration immediately after shutdown has you hanging from the restraint harness, and in a strange position for controlling.

Some of the more subtle effects of the lack of acceleration during simulation are apparent to even experienced X-15 pilots. It is quite common to experience vertigo during various flight phases. Initial rotation to the desired climb angle requires from 20 seconds to, in some cases, 40 seconds depending on desired climb angle. The average rotational g is 2.0. The time required seems much longer than it actually is. The horizon is lost at a pitch angle of about 10° because of the head position and window size. The result is that the pilot is certain he is going straight up and on a number of occasions has pushed over to look for the horizon. This has resulted in low peak altitudes a number of times, particularly when the θ vernier or pitch-attitude indicators have been in error or failed to operate properly.

Also, it is hard to adjust to the duration of high g (3 to 6) required to effect a change in flight path at hypersonic speeds. A pullout from 350,000 feet with a negative 40° flight-path angle at $M = 5.4$ requires an average 5g for 20 seconds. A 10° heading change at $M = 5.3$ requires 3g for 20 seconds.

On the low-g side, an initial climb angle of 25° at a velocity of 3000 fps requires 40 seconds of zero g flight to kill off the rate of climb, during which time the airplane has climbed an additional 40,000 feet.

At low dynamic pressures (less than 100 psf), 90° bank angles for prolonged periods may only result in 10° to 20° heading changes because of the lack of g capability.

These situations are accurately predicted by most six-degree-of-freedom simulations, but seem quite different when actually experienced in flight, because of the tendency to relate g-time situations to previous experience. Subsonic flight experience shows much greater flight-path changes under the same conditions, and you are convinced in most high-velocity situations that you have exceeded the required flight-path change.

Visual.— Visual cues were also omitted in the X-15 simulator. As a result, several important phases of flight could not be realistically evaluated. Approach, flare, and landing have always been accomplished by the pilot using out-the-window information. Using visual cues, the pilot is continually adjusting his situation right up to touchdown, since his capability to judge distances, heights, and closing rates is improving with proximity to the ground. The control rates, frequency of control input, and the amplitudes actually used during an X-15 approach and landing exceeded those used in any other mission phase. These control motions had not been fully appreciated during fixed-base or airborne simulations. Control-surface rate capability was subsequently increased to insure against a possible pilot-induced oscillation during approach, flare, and landing.

A postflare floating problem, peculiar to the X-15 with the adaptive control system, was not anticipated because of the inability to properly simulate flare and landing. This particular problem is a result of the lack of speed stability in a rate command control system. Lack of speed stability was apparent from simulation, but the effects on approach, flare, and landing were not obvious. Airspeed had to be monitored more closely during approach and nose-down trim used to make the postflare control force feel normal during deceleration.

Main-gear landing loads were much higher than anticipated. Realistic landing simulations might have indicated this condition. These excessive main-gear loads were due to a natural pilot control response. As a result of gear geometry, on main-gear touchdown, the nose tended to pitch down rapidly. The pilot and the stability augmentation system responded with increased nose-up stabilizer. The aerodynamic loads produced by the large horizontal-stabilizer deflections added to the rebound loads following nose-gear contact could exceed by 50 percent the initial main-gear loads. A push or nose-down control input is now used to alleviate these aerodynamic loads.

Several other problems have been encountered as a result of the lack of proper simulation of the flight phases in which the pilot uses external vision. One pitfall normally encountered in simulator evaluations of flare and landing was avoided, however. Flare and landing simulations not done in flight tend to indicate the desirability of a flare from maximum L/D as optimum. Even with a visual display, this is generally the result obtained. The reason for this erroneous conclusion is the inability to handle postflare float time. Heights of 2 to 3 feet are difficult to judge even with the best visual displays, and closing rate with the runway, or a tendency to balloon, is not readily detectable.

X-15 performance simulations using an F-104 aircraft during approach, flare, and landing indicated the desirability of having extra airspeed during approach and flare. This additional speed provided better control capability throughout and gave the pilot an extra g margin during flare to adjust his rate of flare as his perception improved near the ground. The postflare time provided by the excess airspeed preflare was useful in making final adjustments prior to touchdown and for extending the gear after flare completion. There is no problem in handling postflare float time during an actual landing. X-15 float times of 15 to 20 seconds are common and, even at the high touchdown airspeeds (190 knots), vertical velocities less than 4 fps are common.

A visual display is not adequate for landing simulation unless it can stimulate the pilot to respond with the same control rates, frequencies, and amplitudes as obtained in flight. The simulation is also not realistic if it does not provide a pilot with the capability to handle postflare floating.

Motion.— Angular motion cues were also omitted in the X-15 simulator. Linear and angular accelerations can affect the pilot's control capability to respond to a particular flight condition. In certain instances the motion cues will assist the pilot in controlling the airplane. In other situations, these same motion cues may cause the pilot to induce, sustain, or feed an airplane oscillation.

A lateral-directional problem encountered in the X-15 with the original tail design gave us an opportunity to evaluate the effect of motion cues on pilot control capability. An F-100C variable-stability airplane was used to further investigate this condition in flight. The results are shown in figure 5. During the initial portion of the time history, the pilot (using a center stick) attempted to hold the stick fixed. The airplane motions caused the pilot to inadvertently apply small control inputs and increase the amplitude of the oscillation. The oscillations damped, however, with hands off. When the pilot attempted to apply conventional corrective control, the amplitude again increased. The use of a side stick in the X-15 alleviated the problem of inadvertent control inputs. An unconventional control technique, which was developed on the simulator and demonstrated in flight, could enable the pilot to control and effectively damp this type of airplane motion. The lack of motion in the fixed-base simulator prevented a full appreciation of this particular problem.

CONCLUDING REMARKS

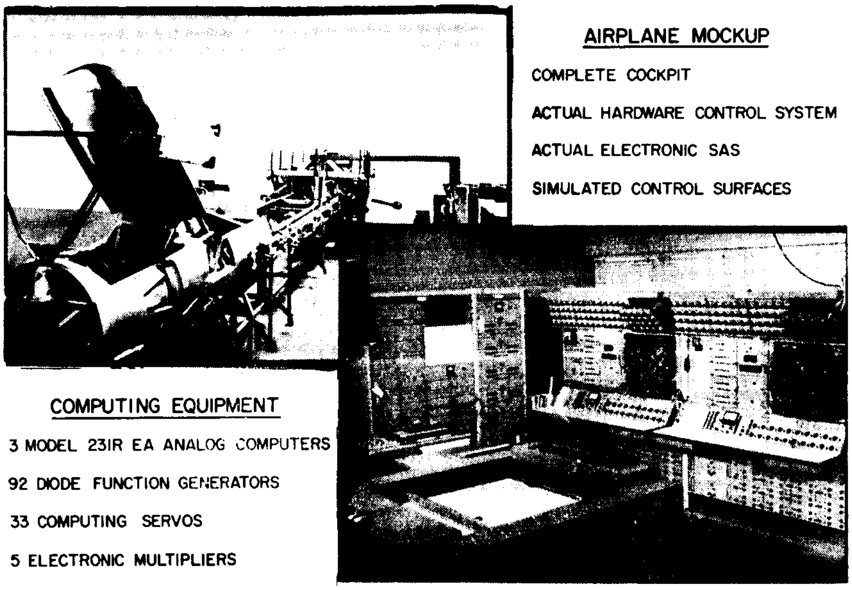
Although relatively sophisticated fixed-base simulation of the X-15 was generally satisfactory for flight-mission studies and flight-envelope-controllability investigations, all of the flight problems experienced were not predicted, particularly when differences in aerodynamics, control system, or cockpit equipment existed between simulator and airplane. A frequent updating of the simulator is therefore required. Absence of acceleration, motion, or visual cues in the simulator has limited the adequacy of pilot training for specific flight phases and sometimes resulted in surprises or in-flight problems.

The actual flight environment must still be investigated, since the effects of apprehension and anxiety on the pilot cannot yet be simulated. It is simple to evaluate a flight condition on a simulator, rate the task subjectively, and reset when you lose control. Until a reset capability is provided in the airplane, the success of a mission is still up to the pilot.

SYMBOLS

a_x	longitudinal acceleration, g
a_z	normal acceleration, g
h	altitude, ft
q	dynamic pressure, psf
t	time, sec
β	angle of sideslip, deg
δ_a	aileron deflection, deg
φ	bank attitude, deg
$\Delta\varphi$	change in bank attitude, deg

FIXED-BASE SIMULATOR



AIRPLANE MOCKUP

COMPLETE COCKPIT

ACTUAL HARDWARE CONTROL SYSTEM

ACTUAL ELECTRONIC SAS

SIMULATED CONTROL SURFACES

COMPUTING EQUIPMENT

3 MODEL 231R EA ANALOG COMPUTERS

92 DIODE FUNCTION GENERATORS

33 COMPUTING SERVOS

5 ELECTRONIC MULTIPLIERS

Figure 1

SYSTEM SATURATION INSTABILITY

M = 5.35; h = 98,500 ft; q = 500 psf

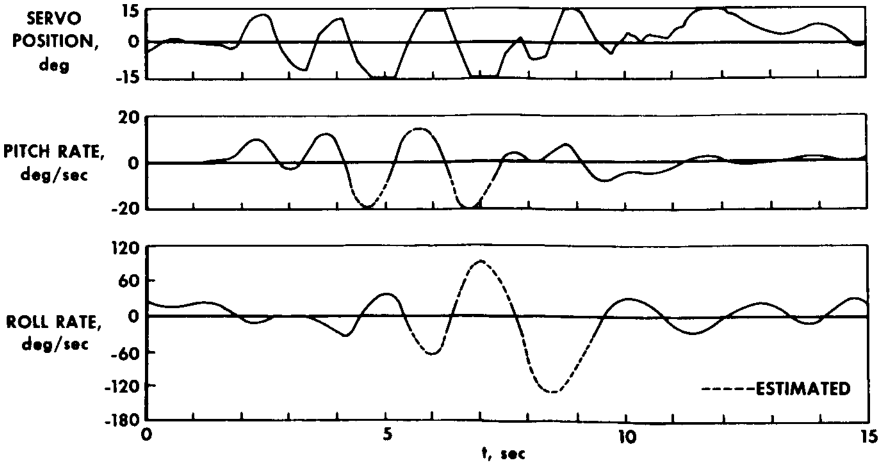


Figure 2

MECHANISM OF VIBRATION

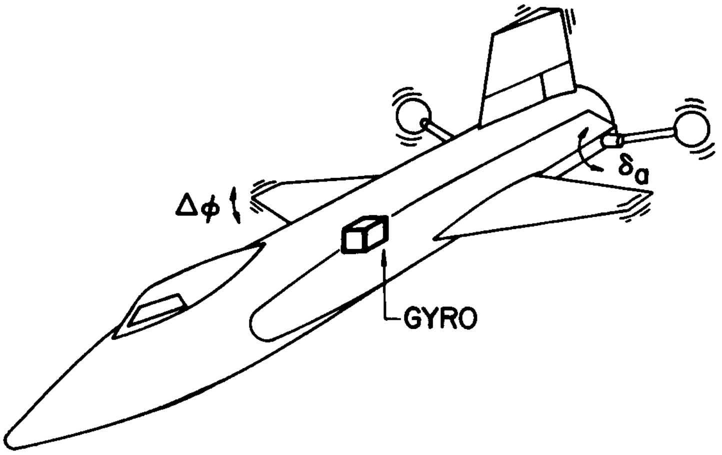


Figure 3

X-15 FLIGHT TO HIGH ALTITUDE

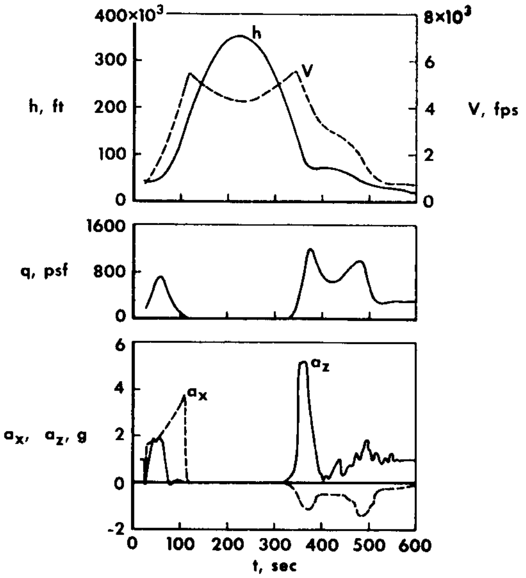


Figure 4

EFFECT OF PILOT ON CONTROLLABILITY
F-100C VARIABLE-STABILITY AIRPLANE

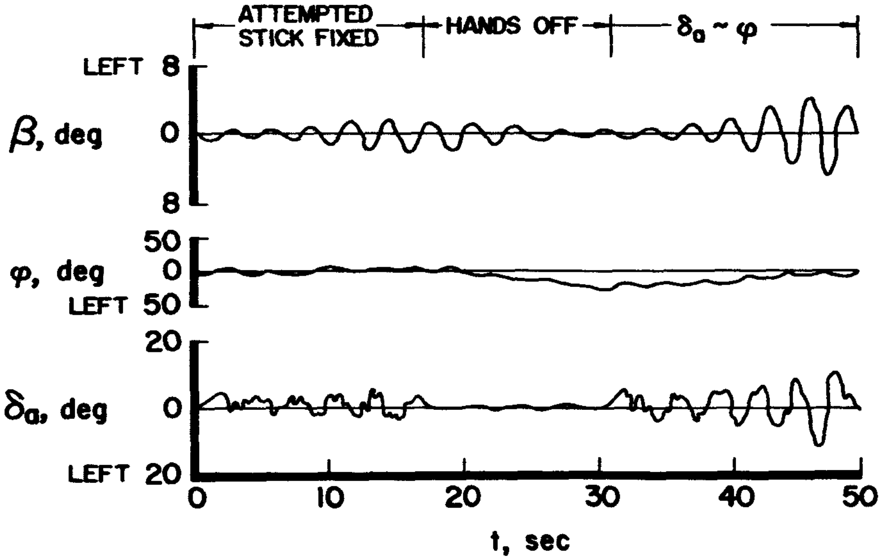


Figure 5