

SIMULATION OF VISUAL AND MOTION CUES
IN AIR COMBAT MANEUVERING *

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BACKGROUND

The Simulation Products Division of The Singer Company is currently developing a Simulator for Air-to-Air Combat (Figure 1). The major components of the Simulator are two F-4 cockpits and two 8-window, wrap-around visual systems mounted on six-degree-of-freedom motion systems, and two target image generating systems. Each pilot will see an electronically generated representation of the terrain, horizon, and sky. His field of view will be limited only by the aircraft structure. The target image generator will provide each pilot with a closed-circuit television image of the aircraft flown by the other pilot, inset in the general visual scene. The target will be seen in the proper attitude and bearing and at the proper range, and in the configuration established by its pilot; the status of speed brakes and afterburners will be represented by working hardware on the televised model.

Proprioceptive cues will be provided to each pilot by the cockpit motion system, and by an operating G-suit, a seat vibration system and a G-seat system.

During the spring, summer and fall of 1972, three systems considered especially critical to the simulator were evaluated, integrated and re-evaluated. These systems were the motion, terrain visual and G-suit systems. The results of the re-evaluation, the subject of this paper, have been incorporated in the simulator, and other systems are being developed and tested. When the simulator is delivered it will be the result of a series of design, integration, evaluation, modification and re-evaluation efforts conducted within a well-defined and highly structured task context. Further, it will be the result not only of intensive engineering and human factors analyses, but of the extensive, intimate and skillful participation of a number of current F-4 pilots.

PROBLEM

The purpose of this paper is to report the procedures employed in the development, evaluation, integration, and modification of the cockpit motion, terrain visual and G-suit systems, and the major results of the evaluations conducted in 1972. The problem was to develop systems capable of providing relevant cues for air-to-air combat, to evaluate these systems and to progressively integrate them into the simulator.

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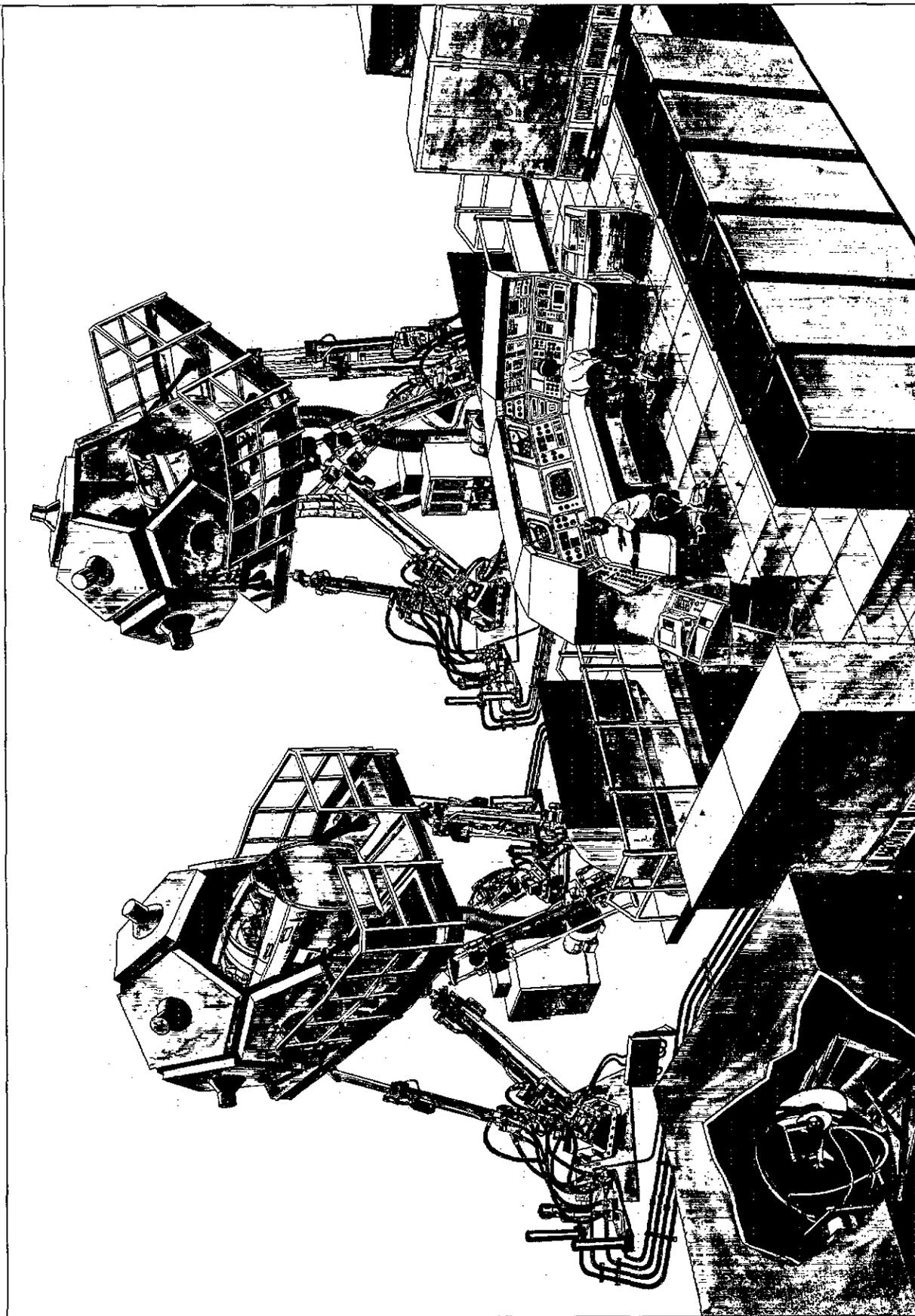


Figure 1. ARTIST'S CONCEPTION OF SIMULATOR FOR AIR-TO-AIR COMBAT

The identification of cockpit motion requirements resulted from analyses of the motions taking place in the maneuvers practiced in air-to-air combat. The F-4 produces accelerations on each of the pilot's body axes, while exercising its repertoire of combat capabilities, in magnitudes significantly above his sensory thresholds. For this reason, a six-degree-of-freedom cockpit motion system was identified to provide as many of these accelerations as possible.

The visual system involved in the motion and G-suit evaluation was designed to provide enough out-of-the-window cues to permit a realistic evaluation of these two systems. Analyses of air combat maneuvers indicated that fighter pilots use the terrain to keep track of and control altitude, attitude, and flight path, and to keep track of and predict the flight path of the target aircraft. Terrain cues are particularly important, when the pilot loses sight of the target, in extrapolating its position after it leaves his field of view. The terrain image concept used in the evaluation displays an electronically generated checkerboard earth surface, of alternate brown and green squares, one mile on a side. The checkerboard changes in size and shape with changes in simulated altitude and attitude. The sky is a featureless blue, with a horizon line between the checkerboard and the sky.

Initial conceptualizations of the cockpit motion system and of its significance in high-performance combat flight indicated a distinct need for cues to sustained acceleration and absolute g-loading on the pilot. The research on g-cue simulation indicated that a G-seat system could provide many cues to sustained acceleration not available in conventional cockpit motion systems, and a G-seat is now being evaluated for the air-to-air simulator. In addition, interview data and initial evaluations of the motion system indicated a need for better cues to absolute g-force than can be supplied by either the cockpit motion system or the G-seat system. The anti-g suit itself appeared promising in providing some cues to g-loading. It is clear that fighter pilots do not use G-suit inflation pressures as primary cues to g-loading but the direct correlation between g-loads and suit inflation appeared to provide at least a possible solution. It was decided to provide suit inflation cues for use as secondary cues to simulated g-loads.

The next step in the development of the simulator was to evaluate individual systems for their ability to provide useful cues, and to be integrated with other proven systems. The motion system and the prototype of the terrain visual system were evaluated, integrated, and re-evaluated. Later, they were integrated in modified form and evaluated together with the G-suit. This integrated evaluation resulted in further changes, which were implemented and re-evaluated. Finally, the simulator was disassembled so that final system designs could be incorporated for further evaluation with the target image generation and display systems.

PROCEDURE

Traditionally, flight simulators have been used to provide practice maneuvers which are well within the operating envelope of the aircraft simulated. Simulators are rarely required to represent flight at high angles of attack, including stalls, spins and aerobatics. As a result, there is little experience available, on the value of specific visual or proprioceptive cues in these flight regimes. For this reason, a series of maneuvers was developed to permit the evaluation of available cues in simulated air-to-air combat maneuvers. Almost all air combat maneuvers are oriented toward the actions of another aircraft, either the one being attacked, or the one attacking. The flight path, configuration and performance of one aircraft are functions of the momentary behavior of the other. This poses two problems for a relevant evaluation: First, an accurate responsive image of the other aircraft must be available; and second, the performance of the simulator being evaluated must be predictable to permit meaningful evaluation by way of standardized performance requirements. At the stage in simulator development at which this evaluation took place, the target image generation system was not available. This made it necessary to develop "canned" maneuvers based on typical performance using the terrain visual system as a reference. This, in turn, made it possible to define specific parameters for each maneuver, making standardization feasible.

In all, sixteen evaluation maneuvers were defined. Thirteen were designed to simulate maneuvers which would be used or might occur in air-to-air combat while tracking, intercepting or evading an opponent. The other three were designed to reveal the stability characteristics of the aircraft as represented in the simulator. All sixteen maneuvers are listed in Table 1, which is a matrix showing the simulator features considered most relevant in each maneuver.

Table 2 summarizes the characteristics of each maneuver. The initial conditions were set from the control console with the simulator frozen. For example, see Figure 2 illustrating the High G Barrel Roll Over The Top. The maneuvers were flown in sets of three or four. Before the pilot flew each maneuver, he was given a pre-recorded demonstration of the maneuver to familiarize him with the instrument, visual, motion and G-suit responses defining the maneuver and to expose each pilot to an identical performance. The demonstration was repeated as many times as required by the pilot. Following the demonstration of the maneuver, the pilot flew the maneuver as many times as desired, usually two or three. Comments made by the pilot were recorded on tape during the execution of the maneuvers. In addition the console operator solicited comments on the simulator characteristics considered most critical in each maneuver. Finally, immediately after completing a set, the pilot completed a questionnaire. Additional discussion of the questionnaire and in-flight responses were recorded in a final debriefing.

The questionnaire was designed to provide data on pilots' impressions of the simulation and to elicit discussion on the quality of the simulation and on feasible approaches to improving it. It was recognized by both designers and pilots that the acceleration environment of the air combat pilot cannot be reproduced in a ground-based device. It was also recognized that useful and in fact vital training could be provided in such a device

Table 1 SIMULATOR CUES FOR EVALUATION MANEUVERS

	PITCH	ROLL	YAW	LONG	LAT	HEAVE	G SUIT	VISUAL
1. SEPARATION MANEUVER	✓			✓		✓	NOTE 1	✓
2. HIGH-G BARREL ROLL OVER THE TOP	✓	✓	✓		✓	Buffet Note 2	✓	✓
3. PITCH STAB AUG CHECK	✓					✓		✓
4. RAPID REVERSAL	Note 2	✓				Buffet Note 2	✓	✓
5. ROLL STAB AUG CHECK		✓						✓
6. LOOP	✓					✓ Buffet	✓	✓
7. 1-G STALL	✓	✓	✓		✓	✓ Buffet		✓
8. SCISSORS		✓	✓		✓	Buffet	✓	✓
9. MINIMUM TIME TURN (19 UNITS/6.5g)	✓	✓				✓ Buffet	✓	✓
10. YAW STAB AUG CHECK		✓	✓		✓			✓
11. BREAK	✓	✓				✓ Buffet	✓	✓
12. LOW SPEED TO HIGH SPEED CONVERSION	✓			✓		✓ Buffet	✓	✓
13. ACCELERATED STALL/POST STALL GYRATION	✓	✓	✓		✓	✓ Buffet		✓
14. LONGITUDINAL ACCELERATION/DECELERATION				✓				
15. MINIMUM TIME TURN (19 UNITS)	✓	✓				✓ Buffet		✓
16. SPIN	✓	✓	✓		✓	✓		✓

Note 1. Depends upon G Suit Offset

2. If maneuver is done properly, the cue is not apparent; if done incorrectly this cue identifies the error

Table 2 PARAMETERS FOR EVALUATION MANEUVERS

MANEUVERS	TRIMMED INITIAL CONDITIONS (1)		MANEUVER BOUNDARIES (IF APPLICABLE)
	ALTITUDE (ft)	VELOCITY (KNOTS)	
1. Separation Maneuver	15000	300	Unload to 3-5 units AOA, Max after-burner (A/B) acceleration to 550 KCAS.
2. High G-Barrel Roll Over The Top	15000	300	Max A/B, no more than 20 units angle of attack (AOA)
3. Pitch Stab Aug Check	15000	350	+2g stabilizer pulse
4. Rapid Reversal	15000	400	From Left Hand Turn (80° Bank, Max 6g or 19 units AOA), unload and roll to right hand turn in approx. 1 sec.; Military Power
5. Roll Stab Aug Check	15000	350	Rapidly roll to 45° bank and release
6. Loop	5000	500	Maximum of 4g or 19 units AOA, minimum of 200 KCAS, Military Power
7. 1-G Stall	15000	200	Throttles - 80% RPM, + 15° pitch until stall
8. Scissors	15000	300	From Left Hand Turn (80° Bank, 19 units AOA) rudder reversal to right hand turn, Max A/B
9. Minimum Time Turn (19 Units) AOA/6.5g	15000	400	Military power, 135° bank, Maximum 19 units AOA, 6.5g, maintain velocity
10. Yaw Stab Aug Check	15000	300	Left rudder to cause 1 ball width deflection to right and release
11. Break	15000	400	To 90° left bank, Maximum 6.5g or 19 units AOA (Alternate 22-23 units AOA)
12. Low Speed to High Speed Conversion	15000	400	Unload to 3-5 units AOA, Max A/B to 1.2 Mach; Roll to 40° left Bank, begin 12 unit AOA climb; at 20° above horizon,

Table 2 (cont'd)

MANEUVERS	TRIMMED INITIAL CONDITIONS (1)		MANEUVER BOUNDARIES (IF APPLICABLE)
	ATTITUDE (ft)	VELOCITY (KNOTS)	
12. (cont'd)			roll to 120° bank, pull back to horizon and level turn
13. Accelerated Stall/Post Stall Gyration	25000	300	From left hand turn (80° Bank, 19 units AOA) use ¼ left stick deflection to depart, then recover
14. Longitudinal Acceleration/Deceleration	15000	300	Military power accel to 400 KCAS: Idle power, Speed brakes decel to 300 KCAS: Max A/B
15. Minimum Time Turn (19 units AOA)	15000	400	Military power, 135° bank, Maximum 19 units AOA, maintain Mach number
16. Spin	30000	200	Throttles -80% RPM, +20° pitch; at stall use ¼ left stick deflection to spin; Receiver after 2 turns

Note: 1 For all maneuvers Weight = 37,500 lb. CG = 27% MAC

FLIGHT CONDITIONS

COMBAT WEIGHT	37,500 LBS
CG. %c	27.
INITIAL: ALTITUDE	15,000 FT
VELOCITY	400 KCAS

PRIMARY CONTROL REQUIREMENTS

1. RUDDER
2. STABILATOR
(ROLL STAB AUG OFF)

MANEUVER BOUNDARIES

INITIAL HARD TURN TO LEFT (19 UNITS AOA): ANGLE OF ATTACK NO GREATER THAN SLIGHTLY SLOW ANGLE OF ATTACK INDICATION

PILOT EVALUATION

THE PILOT WILL BE EVALUATING THE FOLLOWING CUES:

BUFFET/WING ROCK
ANGLE OF ATTACK
G
RATE OF CHANGE OF ATTITUDE

ANALYTICAL DATA ACQUISITION REQUIREMENTS

AIRCRAFT AND MOTION SYSTEM LINEAR AND ROTATIONAL ACCELERATION PROFILES IN ALL SIX DEGREES OF FREEDOM. THE DATA FOR THIS MANEUVER WILL BE USED FOR CORRELATION WITH THE PILOT'S SUBJECTIVE EVALUATION.

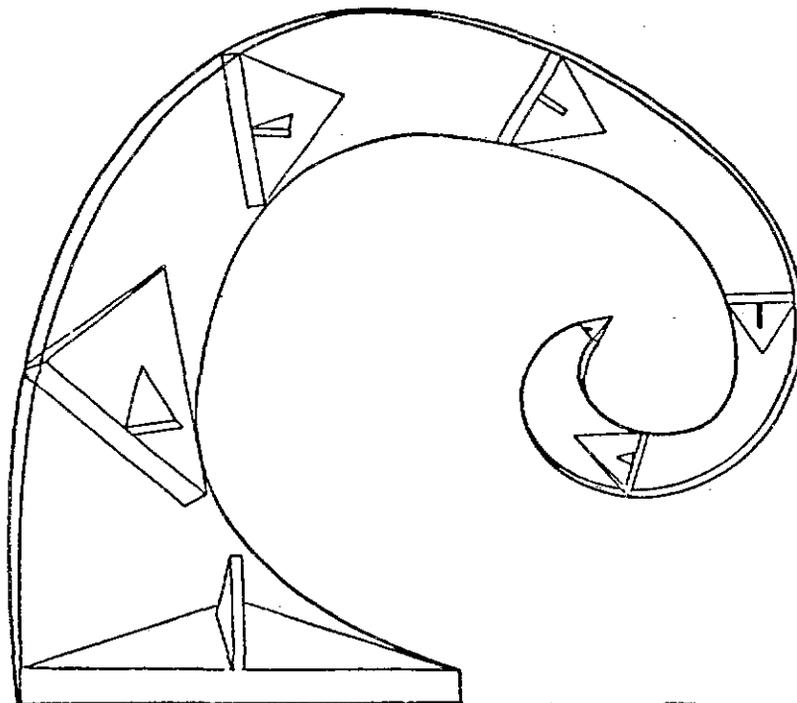


Figure 2 HIGH-G BARREL ROLL OVER THE TOP

if essential cues could be either reproduced or meaningfully represented. A major purpose of the evaluation was to discover ways in which meaningful representations could be developed for those cues which could not be reproduced. Prior to the formal evaluations, information evaluations were accomplished using two in-house engineers who are also current jet pilots. Both have flown the F-4 in combat, but are current in other jet aircraft in the Air National Guard.

In the formal evaluation, two groups of three F-4 pilots flew the simulator in two successive weeks in July. Some comments of the first group, during the first week, were used to modify the simulator for the second group, and the questionnaire was modified to facilitate the collection of more meaningful data. After the second week of evaluation, more changes were made to the simulator and to the motion drive program. In October, two of the original six pilots flew a re-evaluation, using essentially the same maneuvers flown in July. Further refinements were programmed as a result of the re-evaluation. These were implemented during the period in which the simulator was torn down and rebuilt, and the final visual system installed. Further evaluations are being run, but data are not yet available.

RESULTS

The results of the evaluation were quite complex and relatively subjective. Since the questionnaire and the simulator were modified after the first week of evaluation, the results reported here are taken primarily from the second week of evaluation. Some comments made in the first week are included to illustrate the kinds of changes required. The results fall into five major groupings relative to the design of the simulator.

1. Fidelity. The quality of the simulator program, that is, the validity of the software function describing the dynamics of the aircraft, was sensed and criticized in some area by all of the evaluation pilots. Most of the adverse comments about the simulation resulted from incomplete aerodynamic data. Representative comments include:
 - a. Stick forces too light, do not increase properly with airspeed; at high angle of attack, low airspeed, stick forces too heavy.
 - b. Buffet amplitude too high at 12 units angle of attack, frequency too low.
 - c. Can't feel angle of attack in the 17-24 unit area (lack of change of buffet frequency and amplitude).

- d. Do not feel initial yaw before starting roll (scissors).
 - e. Spins easier to recover from in the aircraft, because of the effect of pylons.
2. Buffet Simulation. Many of the comments made by the evaluation pilots concerned the representation of aerodynamic buffet. In some cases the comments resulted from a lack of adequate flight data. Initially, buffet did not change in amplitude and frequency with angle of attack above 19 units angle of attack because data defining this variation were not available. After some of these data were obtained, and/or extrapolated, responses to fidelity were reduced. Some criticisms remained, however, because the structure of the visual display system is limited in its ability to withstand some of the vibrations associated with high angles of attack, thus restricting the buffet allowed. These vibrations are now being incorporated in a vibration system which will act on the pilot's seat, rather than on the entire motion platform.

Buffet cues are used in high performance maneuvering, and particularly in air-to-air combat, to indicate the angle of attack and energy remaining at a given time, to be converted to speed and/or altitude in attacking a maneuvering target, or in evading an attacker. The cockpit instruments display the information required, but pilots do not have the time to review, organize, and employ instruments in air-to-air combat. Once sighted the enemy must be kept in sight. Loss of visual contact may cause loss of the fight. Even in the maneuvers used in the evaluation, when the target image was not available, pilots were only rarely able to look away from the visual scene because of the attitude and rate information it provided.

3. Visual Cues. The intent of the program reported here was to evaluate the six-degree-of-freedom motion system. A visual scene provided cues to attitude, altitude, heading and rates of motion which could not be effectively obtained from interpretations of motion or instrument cues. In the evaluation it was found that the visual scene was essential. The analysis of pilot comments about the visual scene has made it possible to identify requirements which were not originally incorporated. In the evaluation, the only visual cues to altitude and range were changes in the size and perspective of the checkerboard pattern. An initial comment indicated that attending to the pattern near the horizon made azimuth changes appear too rapid. It appeared that a conflict among range cues made the distant scene appear to move faster than it appears in the real world. The borders of the squares in the visual scene were thought of as section lines. In the real world, section lines tend to blend into the haze at a distance, and so do not appear to move past the nose in a turn. In the simulator, these lines were seen out to the horizon, and moved with respect to the nose, producing a conflict in relative range and motion. In effect, squares at a distance, although of appropriate size, appeared to move more rapidly than appropriate because they were of the same color and distinctness as the squares in the foreground. Interestingly, during the evaluation the pilots were able to compensate for this effect, and as the evaluation progressed, it became less of a problem.

In some maneuvers, the pilot is required to "unload" the aircraft, that is, to apply pitch control to go to zero g, to permit converting all available energy to velocity. In the aircraft, this is done by sensing lightness in the seat. In the simulator, visual cues were helpful in controlling pitch rate to that associated with unloading in a given aircraft state.

The questionnaire used to debrief pilots contained spaces for the pilots to check the relative importance of the visual, motion and G-suit cues in controlling each logical segment of each maneuver. Pilots could also note that a particular class of cue was not relevant to a particular maneuver segment. In eleven of the sixteen maneuvers (see Table 3), motion cues were of primary importance; they supplied most of the information needed to fly the maneuver. In the other five maneuvers, visual cues were of primary importance, but in eight of the eleven motion-oriented maneuvers, visual cues were considered of second priority. In three, the Rapid Reversal, the Break and the Accelerated Stall/Post Stall Gyration, G-suit cues were of greater value than visual in supplementing the information derived from the cockpit motion system.

The questionnaire responses indicated visual cues were applicable in almost all segments of almost all maneuvers. Only about 11% of all the possible "Not Applicable" responses were made for visual cues. Further, about 70% of the possible responses indicated that the visual cues provided were adequate for the maneuver segment flown. Perception of altitude and altitude rate was difficult for all of the pilots until they had become calibrated in the appearance of the checkerboard squares. In the loop and in the barrel roll, limitations in field of view caused problems, which pilots compensated for by looking at the attitude indicator, which, of course, would rarely be possible in air-to-air combat.

4. G-Suit Cues. The G-suit was considered an important source of cues to control in a few maneuver segments. In the aircraft, the G-suit exerts pressure on the pilot, beginning at +1.75 g's and increasing at the rate of about 1.3 psi/g to 10 g's. In the simulator, the pilot's body does not expand into the G-suit as it does in the aircraft when exposed to positive-g forces; thus, he tends to be more sensitive to G-suit pressure and must use less pressure at the same g level for the same G-suit "feel". The G-suit program was adjusted during the orientation flight to provide the pressures preferred by the pilots. Two pilots used a 1.75 g offset; that is, the system was programmed for zero psi at 1.75 g, increasing at 0.7 psi/g. One pilot used a program of zero psi at zero g with the same 0.7 psi/g gradient. The questionnaire data show that there was no difference between pilots using the 1.75 g offset and the pilot using the zero psi at zero g program in judging G-suit cues as adequate and useful. The only difference was in establishing and maintaining zero g.

Table 3 CUE PRIORITY FOR EVALUATION MANEUVERS

MANEUVER	CUE PRIORITY		
	MOTION	VISUAL	G-SUIT
1. Separation Maneuver	2	1	NA/3
2. High-G Barrel Roll Over The Top	1	2	3
3. Pitch Stab Aug Check	1	3	2
4. Rapid Reversal	1	3	2
5. Roll Stab Aug Check	2	1	NA
6. Loop	3	1	2
7. 1-G Stall	1	2	3
8. Scissors	1	2	3
9. Minimum time Turn (19 units AOP/6.5g)	2	1	NA
10. Yaw Stab Aug Check	2	1	NA
11. Break	1	2	3
12. Low Speed to High Speed Conversions	1	2	3
13. Accelerated Stall/Post Stall Gyration	1	3	2
14. Longitudinal Acceleration/ Deceleration	1	2	NA
15. Minimum Time Turn (19 units AOA)	1	2	3
16. Spin	2	1	NA/3

G-suit cues were considered to be essential in supersonic maneuvering where it is easy to overstress the aircraft without good cues to g-forces.

5. Cockpit Motion. About 4% of the possible responses in the questionnaire on the applicability of motion cues in the control of the seventeen evaluation maneuvers indicated that cockpit motion was not really relevant. Most of the "Not Applicable" responses were in the separation maneuver, which involves relatively limited motion in pitch and heave. In general, cockpit motion cues were considered the most important of the three systems in supporting flight control, with one-half of the possible responses to the "1st priority" item. Cockpit motion cues were generally considered good. Pilots were not asked specifically to judge the quality of motion in and around each cockpit axis, but other comments indicated sensitivity to the quality of complex motions. Longitudinal accelerations were used, for example, to predict pitch requirements in achieving and maintaining specific angles of attack, altitude and g-load in afterburner light-off. Initially, afterburner simulation caused problems in control because the data indicated a greater lag between throttle position and airplane response than was in fact typical. In rapid rolling maneuvers, pilots noticed that adverse yaw in rapid aileron rolls was not correct at first. In the barrel roll, one pilot noticed that buffet represented in the simulator along the longitudinal axis, with no buffet along the lateral axis. In the yaw stab aug check, pilots noticed the sliding in the seat, resulting from the lateral component of yaw which results from the placement of the seat ahead of the aircraft's center of yaw rotation.

A major problem was encountered in the simulation of pitch in the loop. The loop requires a positive acceleration (through the z-axis) throughout the maneuver over an appreciable period of time. The simulator is programmed to pitch as a nonlinear function of pitch and pitch rate reaching a maximum of $+30^\circ$ platform pitch up and -20° platform pitch down. This program is valid both for inverted and normal attitudes. Thus, in a loop in which pitch exceeds 90° , the cockpit settles to neutral (0° pitch) as the aircraft comes over the top on its back. As the nose goes below the horizon, inverted, the simulator pitches down, pitching back up as the nose goes through the vertical and rises toward the horizon on the recovery. Throughout most of the maneuver in the aircraft, a positive acceleration of about +4 g's is maintained.

Because the simulator cannot achieve sustained positive g, or become inverted, the pilot experiences pressure on his back at the beginning of the loop, even though the pressure should be in his seat. In the last half of the loop, he feels pressure against the seat belt, which he should also feel in his seat. An attempt was made to correct the problem by reducing the ratio of simulator pitch angle to aircraft pitch angle, but this left insufficient pitch to permit control of other maneuvers. It was concluded that perfect simulation of pitch is not possible with a conventional cockpit motion system. Pilot

comments indicating that the G-suit provided useful cues, and comments on the sensing of seat, seat belt, and seat back pressures in the loop suggest that a much higher degree of simulation fidelity will result from the incorporation of a G-seat system. This system will provide differential pressure on the seat cushion and the seat back to simulate sustained accelerations, to supplement the onset cues provided by the cockpit motion system and to reinforce the G-suit representation of sustained accelerations.

During the evaluation, although not as part of it, an attempt was made to provide longitudinal accelerations by means of a gravity alignment program. The simulator was programmed to pitch up to provide the positive acceleration cues along the longitudinal axis accompanying such events as afterburner actions. The simulator pitched down to provide the seat-belt pressure and the reduction of pressure on the seat back accompanying such things as speed brake deployment. It was found almost immediately that pilot thresholds for pitch rotation were so small that this program produced conflicting cues which could not be eliminated by re-scaling. When the cockpit was pitched forward to simulate deceleration, pilots invariably increased back stick pressure to cancel what they sensed as a pitch-down before they had time to interpret the cockpit instruments or the visual scene.

6. Vibration and G-Seat. The cues to angle of attack available in the airplane, in effect, the cues to energy remaining at a given time, range from a vibration at around 11-12 units of angle of attack to a strong buffet at the high range, around 25-30 units. Pilots were able, when the simulator program was updated, to discriminate angle of attack within one or two units from around twenty to thirty units. The vibrations at the low end could not be programmed because of their effect on the visual display system hardware. As a result, cue capability in the low angle of attack is being provided by a system which will vibrate the pilot's seat without influencing the visual system hardware. This will permit precise control of available energy in complex maneuvers without requiring reference to the cockpit displays.

The G-seat will facilitate control of g-forces on the simulated aircraft. The G-suit provides some of the cues needed to train in avoiding overstressing the aircraft, but flight at zero-g is required in converting available energy to velocity. Pilots use lightness in the seat during zero-g acceleration. The G-seat will provide some of the cues denoting lightness. Also, the G-seat will provide changes in seat belt pressures to simulate positive and negative accelerations along the longitudinal and vertical axes. The motion evaluation indicated that these cues are required in assessing the performance of the afterburner and speed brakes, and in compensating for the lack of real positive and negative g-forces in over-the-top maneuvers. Differential inflation of seat and back cushion cells will also provide sustained cues to slipping and skidding which are not available in any other system. These will be particularly important in the gunnery phases of air combat maneuvering in maintaining balanced flight during weapon delivery.

CONCLUSIONS

A bare minimum of information is available on the significance of cockpit motion in the simulation of high-performance aircraft in marginal flight regimes. Experience indicates that cockpit motion is essential in training most complex flight skills. Experience also indicates that out-of-the-window visual information influences the perception of cockpit motions. The analysis of maneuvers flown in simulated air-to-air combat indicated a need for specific motion and visual cues. A review of simulator capabilities indicated that some of these are not available, and most have never been evaluated in air-combat-like maneuvers. The maneuver analysis indicated a need for eight kinds of cockpit motion:

- Pitch - to simulate climbs, dives and changes in airspeed and altitude, also pitch rate, to permit accurate control of hard turns.
- Roll - to represent changes in attitude in aerobatics/ACM and in the initiation of heading changes.
- Yaw - to represent changes in heading and the coordination of rudder and aileron inputs in some flight regimes (i.e., high angle of attack when rudder is used for roll control instead of aileron).
- Heave - to simulate the movement arm around the lateral axis, in pitch due to the pilots location ahead of the axis of rotation.
- Longitudinal translation - to provide cues to accelerations and decelerations along the flight path.
- Lateral translation - to provide the lateral component of yawing motions around the vertical axis because the pilot is located ahead of the axis of rotation.
- Airframe buffet and vibration - associated with various angles of attack, signifying aerodynamic flow separation.
- Sustained accelerations - along and around each axis, resulting from attitude and velocity changes in complex maneuvers.

The evaluation of the air combat simulator motion system was programmed to define and refine systems for providing these cues to aircraft motion. The evaluation phase reported here exposed current and highly skilled F-4 pilots to motions in all flight regimes encountered in air-to-air combat, so that they could evaluate a cockpit motion system, a terrain visual system and a G-suit system. Pilot comments and responses to a questionnaire indicated that:

1. The simulation of high-performance maneuvers requires very high-fidelity aircraft data. Many of the pilot comments resulted from imperfections in aerodynamic data, particularly in the high-g, high angle of attack regimes. Pilots were confused when they made inputs which would normally produce changes in buffet, stick forces or attitude, when these changes did not occur as expected. In some instances, this induced pilots to scan the instruments, or to make

erroneous corrections or to modify or terminate inputs, all of which reduced combat efficiency and degraded the performance of the maneuver. When corrections were made to the data, most comments disappeared.

2. The simulation of buffet and vibration is essential in the simulation of flight near the edge of the performance envelope in the F-4 aircraft. A pilot flying a non-buffeting F-4 simulator could not accurately perform any of the maneuvers flown at over 10 to 11 units angle of attack without extensive instrument reference. In air-to-air combat simulation, he could not compete with another pilot in a simulator having a buffet program, because he would lose sight of the other aircraft. Without looking at the cockpit instruments, it would be impossible for him to select the precise angle of attack required to convert or dissipate energy as required to evade or attack. Further, it is apparent that a pilot flying a simulator with a partial buffet program would have to fly well within the flight envelope to avoid stalling, making him vulnerable to a better-equipped opponent, or he would have to risk stalling, making him even more vulnerable. While transfer studies have not been accomplished with respect to fidelity requirements on the buffet program, it is expected that anything but complete simulation of buffet would be pointless in preparing pilots to make best use of their aircraft in air-to-air combat.

The development of this simulator has indicated that a useful level of F-4 buffet simulation cannot be provided in the cockpit motion system alone. The addition of a vibration/buffet system is required to provide essential cues to differences in angle of attack without overstressing the simulator structure.

3. Visual simulation is essential in providing the pilot with a perspective in which to use and evaluate cockpit motion stimuli. It was apparent that pilots could not execute the maneuvers employed in the evaluation through reference to the cockpit instruments and the motion system alone. The instruments were used to establish the initial altitude and airspeed required, but attitude and heading were controlled almost entirely by visual reference. Loops were difficult at first, for example, because the pilots had to look at the ADI when the visual scene disappeared due to the limited field of view. While this permitted the pilots to perform satisfactory loops, it would be unacceptable in air-to-air combat simulation.
4. The G-suit provides some unique cues to the absolute magnitude of g-forces, and to the rate of build-up and bleed-off of g-forces. They help train the pilot to avoid overstressing the aircraft, and to control pitch changes for optimum conversion of energy to speed or altitude. They also help indirectly in the control of angle of attack in reinforcing the buffet cues provided by the cockpit motion system.

5. Motion in each of the six degrees of freedom provided by the cockpit motion system is required to support control of simulated high-performance flight. The evaluation involved maneuvers in which altitude, airspeed, angle of attack, g-load, attitude and heading parameters defined the maneuvers to be flown. Except when setting up the simulator to begin a maneuver, pilots were rarely able to divide their attention between the visual scene and the cockpit, even though all of the information required to control these parameters was clearly displayed on the cockpit instruments. The rapidity with which air combat maneuvers must be flown, instrument lag, and the time typically required for instrument interpretation made it necessary for the pilot to glean as much information as possible from other sources of data on aircraft status. Each of the six degrees of cockpit motion was involved in this process:

- a. Pitch. Motion in pitch was an immediate cue to changes in airspeed, angle of attack, attitude, altitude and altitude rate.
- b. Roll. Roll motion was important in establishing a flight path and g-loads designed to maximize the capabilities of the simulated aircraft without wasting energy or altitude and without exceeding the structural limits of the aircraft. Strong visual cues were available in the form of a distinct horizon line, but they were not adequate in controlling rapid roll rates. Also, the horizon was not always available for reference, making motion even more critical. Visual cues alone were not adequate in the high-speed context of air combat maneuvering in supplying roll information.
- c. Yaw. The visual cues to yawing motion in actual air combat maneuvers are not particularly useful, except at low altitude in well-textured terrain. In many maneuvers, visual cues are totally lacking due to the orientation of the aircraft. Information about yaw was significant in establishing and maintaining control because it correlated with changes in heading and because it was a cue to aircraft performance and flight status. In the accelerated stall, and in the post-stall gyration, buffet was used to sense the impending stall, but a distinct yaw, which is the immediate cue that the aircraft has in fact stalled, did not occur. As a result, the pilots thought that some lift remained to be converted to speed or an increase in altitude. As a result, they were unable to react correctly until the nose slice was simulated.

At high angles of attack, adverse yaw accompanies the initiation of a turning maneuver with ailerons. In rapid maneuvers, and where there was no fixed outside reference, yaw motion was the only cue available to the start of the turn. The absence of yaw motion would indicate that either the rudder input was too small or that angle of attack was lower than intended.

- d. Heave. The position of the F-4 pilot approximately 16 feet ahead of the center of pitch rotation, the lateral axis of the aircraft,

makes each pitch motion also motion along the pilot's z-axis, or heave. Airframe buffet was felt primarily in heave, i.e., along the z-axis. Buffet was an important cue to angle of attack and to the rate of energy dissipation.

If heave motion WAS missing, pitch would be an abnormal pure rotation which the pilot would interpret as too small a control response causing over control. If buffet WAS to be felt in the pitch axis, it would further confuse the cues to pitch change.

- e. Lateral. The aircraft yaws about its vertical axis, which, like its lateral axis, is behind the pilot by some 16 feet in the F-4. Almost all changes in heading, then, result in pilot motion in yaw, and displacement along the pilot's lateral axis. In some maneuvers, particularly skids and slips, the major motion component is along the lateral axis, and is an immediate and direct cue to uncoordinated flight, whether intentional or inadvertent. The lateral motion accompanying adverse yaw and a nose slice gave definite cues of potential loss of control in departures and post-stall gyrations. Some buffet occurred along the lateral axis, and in one case pilots noted that all buffet had been programmed along the longitudinal axis, making it difficult to sense the normal build-up of buffet causing a slight lag in response to the angle of attack simulated.
- f. Longitudinal. Longitudinal accelerations were cues to the operation of afterburners and speed brakes informing the pilot on whether these systems were in fact producing the effect desired in rapidly changing airspeed or altitude. The cues provided by longitudinal motion gave instantaneous feedback on the magnitude of thrust changes and the rate of change of acceleration, allowing the pilot to make accurate responses without looking back into the cockpit.

Visual and instrument cues occurred too late to be relevant, and aural cues did not provide the rate information required to maintain effective control.

ABOUT THE AUTHORS

DR. EDWARD A. STARK received his PhD in Psychology from the Ohio State University in 1955. Prior to first joining Link Aviation, Inc. (now Singer-Simulation Products Division) in 1959, he was employed by HumRRO, where he conducted research in the training of infantrymen and tank crews. From 1960 to 1966, he was associated with IBM's Federal Systems Division, and the Bell Aerodynamics Company, as an Engineering Psychologist, where he was responsible for human engineering of V/STOL cockpits, avionics systems and missile guidance systems. He also participated in the development of a training program for air cushion vehicle operators. Since returning to Link in 1966, Dr. Stark has performed a number of analyses of simulation requirements for training tank, helicopter, fighter and ASW crews. He was Singer's Principal Investigator on a Naval Training Equipment Center study of the Navy's Undergraduate Pilot Training System, and was responsible for human factors support in the development of the Air Force's Advanced Simulator for Undergraduate Pilot Training research. He was also Principal Investigator on a NAVTRAEQUIPCEN Study to define an Experimental Training Simulation System. Dr. Stark and Mr. Wilson are responsible for the design, conduct and analysis of pilot evaluations of various systems in the Simulator for Air-to-Air Combat.

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