A Manned Air-to-Air Combat Simulator

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This paper discusses the development of a simulator which utilizes two cockpits equipped with individual instruments, controls and visual displays. The objective is to provide a new means of evaluating airplane capabilities in air-to-air combat. Either pilot can maneuver, within his airplane's flight envelope, against the opposing airplane. All computation is by digital computer. A collimated display for each cockpit presents the opposing airplane, the gunsight and the earth. The images are "stroke written" by a Schmidt cathode-ray tube projector. An 80° field-of-view limitation is circumvented by presenting a mirror view when the opposing airplane is in a chase position and a "radarlike" synthetic display when it is not within the forward or aft 80° cone. Future developments will display the opposing airplanes' positions on the inside of spheres enclosing each cockpit.

Nomenclature

$\mathcal{R}$ = aspect ratio
D_B = drag in body axes
C_{D_0} = zero lift drag
e = airplane induced drag efficiency factor
g = gravitational acceleration
I_x = moment of inertia about x axis
I_y = moment of inertia about y axis
L_B = lift in body axes
$\mathcal{L}$ = rolling moment
$\mathfrak{M}$ = pitching moment
n_z = normal load factor
p = angular rolling velocity
q = angular pitching velocity
q = dynamic pressure
r = angular yawing velocity
S = wing area
T = thrust
u = velocity along body x axis
V = velocity along flight path
w = velocity along body z axis
W = airplane weight
ϵ_T = angle between thrust axis and body x axis
ϕ = roll attitude
θ = pitch attitude
ρ = range between airplanes

I. Introduction

A SIMULATION facility for air combat experiments is currently being developed by Computer Technology Incorporated and the Vought Aeronautics Division of the LTV Aerospace Corporation. It provides two single-seat fighter/attack-type cockpits with individual instruments and controls and with interconnected visual displays.

The initial objective of the air combat simulator is to develop and verify this means of evaluating airplane capabilities in air-to-air combat situations. The two cockpits are manned by experienced fighter pilots and/or pilot-engineers. Starting from selected initial conditions, the pilots compete against each other until one is scored as winner. It is intended that through this means the effects of such factors as airplane performance, maneuver limitations, and armament system capabilities on the success of an air-to-air encounter can be evaluated in a more realistic manner than has been heretofore possible.

Vought Aeronautics Division initiated this program in February 1967 by utilizing two visual display systems that were developed by the LTV Computer Center and the Vought Missiles and Space Division for a Lunar Module simulation in conjunction with the Apollo Program. The LM Simulator visual systems were used successfully under contract to NASA during the period from June 21, 1965 to final report addenda submission in February 1967.

The visual display system, illustrated on Fig. 1, consists of a Schmidt cathode-ray tube projector that projects onto an inclined mirror to a beam splitter to a screen which is viewed through collimating lenses. The projector consists of a cathode-ray tube that projects into a spherical mirror, then back through a corrector lens to focus the image. The field-of-view as used in the LM Simulator was approximately 80° with the viewer's eye 17 in. from the collimating lenses.

Prior to development of the air combat simulator, there were questions concerning the technical feasibility of digitally derived information for visual display purposes in this type of problem, because of the very high relative velocities that can occur between airplanes. Also, the rather restricted, forward only, field-of-view of this approach produces certain limitations in operational flexibility of the simulator. However, it was decided that proof of principle could be demon-

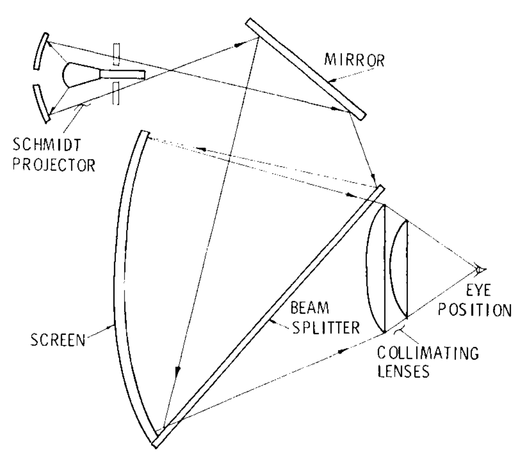

Fig. 1 Visual display system schematic.

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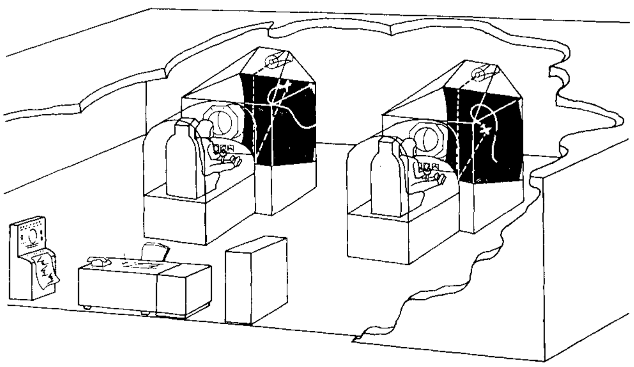

Fig. 2 Prototype air combat simulator.

strated at a substantial savings in time and cost by using the visual systems available from the Apollo Program. Limitations imposed by this approach were accepted and operating procedures were developed to define a useful set of evaluation conditions.

II. Simulator Description

An artist's drawing of the simulator in its prototype configuration is shown on Fig. 2. Each cockpit is provided with identical equipment and display capability. The pilot of airplane A sees a visual presentation of airplane B, the earth horizon, and a gunsight. At present, the simulator is mechanized for the gun-only case, and when pilot A pulls the trigger he sees his own tracer bullets progressing to the target B airplane. The stick and visual scene are "jiggled" to represent airframe buffet. Either pilot is able to maneuver within his airplane's flight envelope to either attempt to escape or to attack the opposing airplane. The computer provides proper airplane-to-airplane and airplane-to-earth orientation as functions of the control actions of both pilots.

Hardware Description

Hardware elements of the simulator consist of the visual systems, the cockpits with controls and instruments, and a digital computer with suitable peripheral equipment.

Visual systems

A photograph of one of the visual systems mounted on an F-8 cockpit is shown on Fig. 3. Side panels are removed to show the relationship of the mirror, beam splitter, screen, and lens system. Realism and three-dimensional effects are provided by the collimating lenses. The heart of the display is the Schmidt projector shown on Fig. 4. Information is presented to the projector at a rate of 20 times per second. Persistence of the phosphor on the CRT smooths the image and gives the illusion of continuous motion.

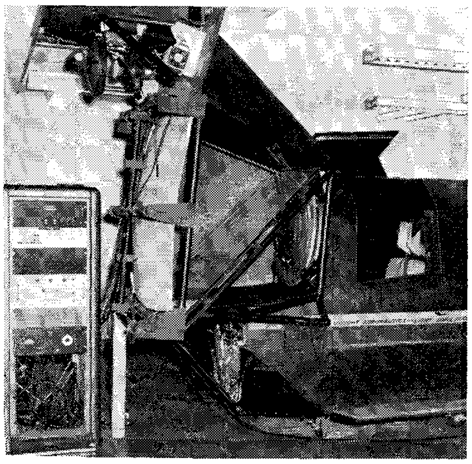

Fig. 3 Visual system.

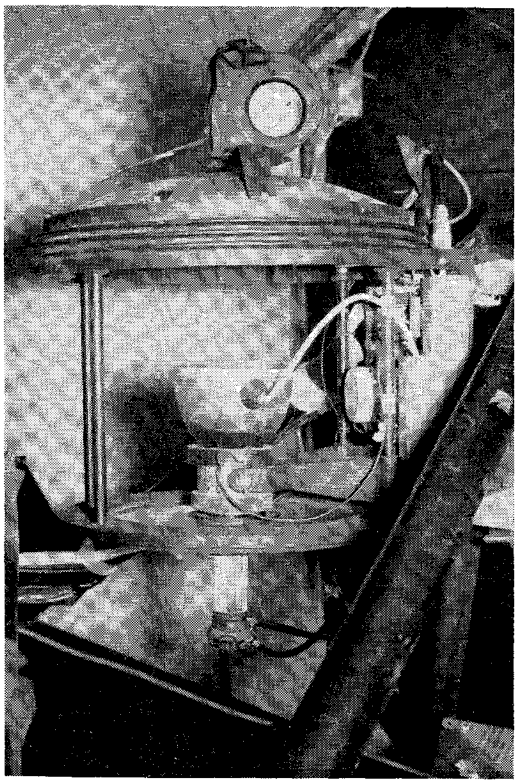

Fig. 4 Schmidt projector.

The visual display systems are mounted forward of each cockpit in a position such that the collimating lenses do not interfere with the view of the instrument panel. This places the collimating lenses approximately 2 ft ahead of the normal eye position. In this position, the field-of-view is approximately 60°; however, by leaning forward a few inches, as one would naturally do in combat, the full 80° field-of-view of the system is available. Figure 5 shows the cockpit, pilot, and visual system interface. This illustrates the total field-of-view that is available for experiments which utilize the prototype equipment. The Software Description section discusses the rear-view mirror and synthetic display that are employed to circumvent the limitation imposed by a field-of-view that is less than that normally available to a fighter pilot. The Future Development section discusses planned hardware changes that will circumvent the restriction in a more realistic manner.

Cockpits

Several alternatives for crew accommodations were available for this program including the use of the Manned Aerospace Flight Simulation Facility (MAFS); a device that provides acceleration cues in roll, pitch, and yaw. Although motion cues might be a valuable asset to this type of simulation, the job of adapting the existing visual system to a moving base would have required extensive redesign of the visual system and the MAFS. Also, only one moving base facility was available and two cockpits are employed in this simulation. The decision was to devote maximum attention to the system problem as a whole and not concentrate on this particular aspect.

An F-8 and an A-7 nose section, which were available from other simulation and mockup activities, were selected for the cockpits. These were installed fixed based in the simulation laboratory. A view inside the modified F-8 cockpit is shown in Fig. 6.

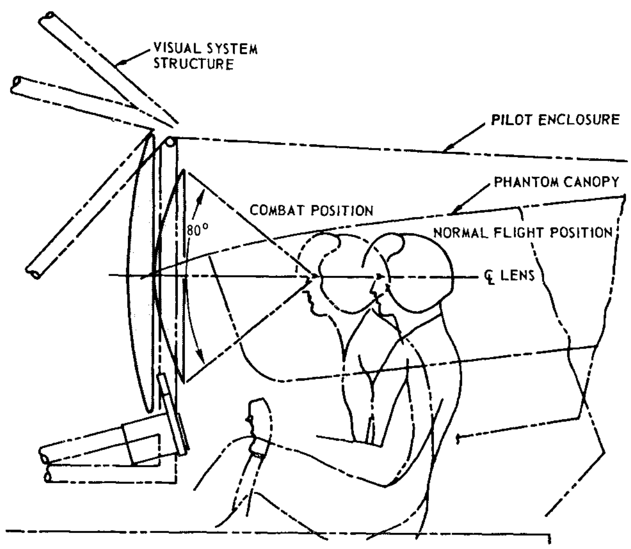

Fig. 5 Field-of-view geometry.

Instruments

The instruments provided in each cockpit are: altimeter, airspeed/Mach meter, rate of climb, attitude ball (pitch, roll, and yaw), normal accelerometer, pitch trim, wing-sweep position, fuel remaining, and speedbrake indicator. The flight instruments are adapted from real instruments and have synchro drives fed by digital synchro translators. The wing-sweep position and fuel remaining indicators are voltmeters. The speedbrake indicators are simply situation lights.

Controls

Each cockpit is equipped with real airplane controls. These are: two-axis control stick with beep trim switch and trigger, rudder pedals, throttle with afterburner control and speedbrake switch, wing sweep control handle, gunsight uncage switch, fixed or radar range switch and seat height control switch. Intercom and computer control switches are also provided. Control feel forces are obtained by mechanical springs. Parallel pitch trim with beep control is provided in each cockpit.

Computer equipment

The computer equipment employed consists of the following principal devices, all are slaved to the Central Processing Unit (CPU):

1) Scientific Data Systems SDS-930 digital computer with 16k memory; 2) SDS, six-bit-character, 500kc, 1800 rpm fixed-head magnetic disk; 3) SDS, 600 line per minute, buffered line printer; 4) SDS, 96kc magnetic tape unit; 5) SDS paper tape In/Out unit; 6) multiple-access-to-memory channel with two data subchannels providing analog conversion and visual system multiplexing to one memory bank; 7) analog to digital, digital to analog, digital to synchro, clocking, interrupt and discrete In/Out linkage equipment; 8) vector, dot, circle and alpha-numeric graphic generation equipment; 9) approximately 80 amplifiers of Electronics Associates general-purpose analog computer equipment.

Software Description

Development activities were required to write the software programs for the visual displays, the airframes, and the space coordinate transformations. Previous investigators in this field have encountered the problem of excessive computation time vs the real-time line-of-sight rates produced in air combat encounters. The results of this situation can be an unnatural dynamic response of the system, producing sluggish and poorly damped reactions to input commands. Continuous care was exercised during the software development program to limit sequential computations where practical through simplifying assumptions. Fixed-point assembly-language routines which were time optimized have been used throughout. A situation update rate of 20 times/sec is used.

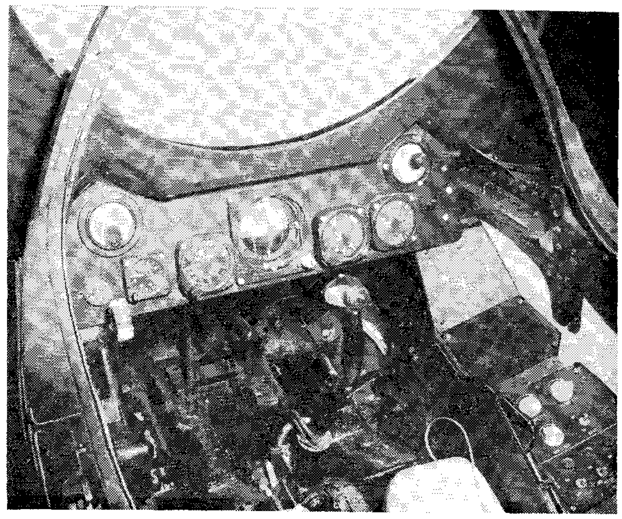

Fig. 6 Simulator cockpit.

Visual system software

General requirements for the visual system are small area, high-information density for aircraft, gunsight, and tracer bullet images, and large-area, low-information density for earth and atmosphere images. The approach to visual software can be illustrated by describing the procedure for generating the aircraft image. Other elements of the scene are similar in principle, though not in detail.

Aircraft

The aircraft images are digitally defined and stored on a rapid-access fixed head disk. Access time to any data block on this disk is at most 33 msec. The data stored on the disk represents the body-fixed coordinates of the line end points for each elemental line making up the geometric aircraft body and includes only those lines or line segments that are visible at a particular relative viewing aspect of the body. The data organization is of the form shown in Fig. 7 where the stored coordinates represent the line-element geometry of a body such as Fig. 8.

The mode and line identifier bits serve to identify to the image readout device the nature of the line to be drawn be-

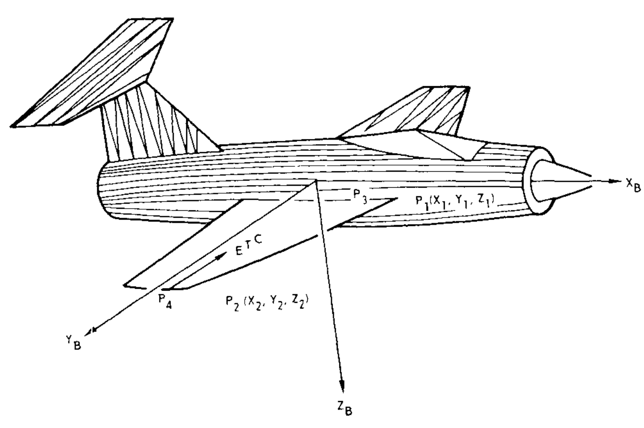

Fig. 7 Data organization.

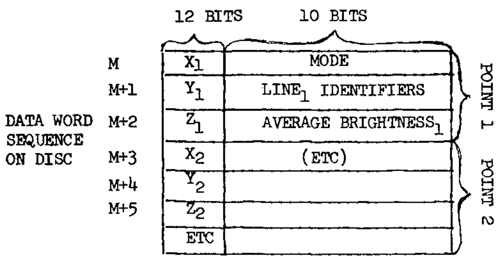

Fig. 8 Aircraft image generation.

tween the points. Representative information about a single line is: 1) type, straight line, circle, dot, null (blanked) line, etc., 2) start of data for a body variable feature such as a particular position of wing sweep, etc., and 3) end of a data block signaling an interrupt request to the CPU, change to another body, or transfer of control.

The organization of view data on the disk is grouped into viewing aspects using a regular sequence of eye points in forming the parametric family of views. The viewing aspect-set is as shown on Fig. 9, where the increments $\Delta\theta v$ and $\Delta\phi v$ are selected to provide a nominally constant angular spacing between views as measured on the surface of the range sphere. The set of data so formed represents the solid body viewed from many possible aspects at a range ρ.

The data set of all viewing aspects of both aircraft is stored in a one million six-bit-character fixed head disk. As the problem calls for a particular viewing aspect, it is pulled into the core memory and then fed to the CRT projectors as schematically shown on Fig. 10. Varying range between aircraft in true perspective is presented by controlling the gain of the high-speed analog matrix operator. Typical views of aircraft images generated as described and projected by the visual system are shown on Fig. 11.

Earth representation

The Earth representation employed is drawn by the Schmidt projector and provides roll, pitch, and heading cues to the pilot, but does not provide altitude or translational velocity cues. As is illustrated on Fig. 12, the flat earth is represented by an open inverted hexagonal pyramid with the pilot's eye in the center of the base. The pyramid is fixed in pitch, roll, and yaw relative to earth axis, but travels with the pilot's eye. In level flight, the pilot sees a horizon line and a vertical line representative of a road leading away from him. When he dives straight down, he sees the intersecting lines at the apex of the pyramid. This simple representation has proven quite satisfactory thus far. It would be desirable

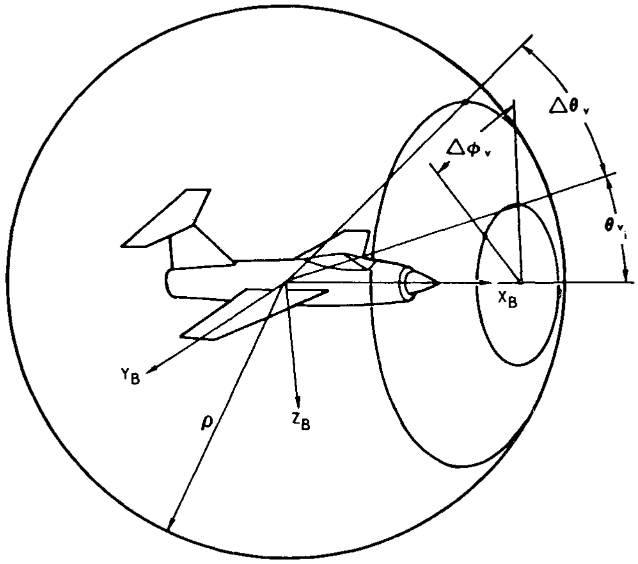

Fig. 9 Viewing aspect set.

to have a pattern that would grow in size as altitude is decreased to add an altitude cue.

Gunsight and tracers

The gunsight display shown on Fig. 13 is also drawn by the Schmidt projector. It consists of fixed 50- and 100-mil rad rings, 45° bank reference lines, a 10-mil-diam pipper, a nonlinear 10,000-ft range scale, a range marker and an in-range reference bracket. The pipper and range marker are driven by the computer when the sight is "uncaged," the range switch is in the "radar range" position, and the radar is "locked on" (within radar envelope). When the pipper is superimposed on the target airplane, the lead angle for a lead pursuit trajectory is provided. The pilot can fire when the range marker is within the "in-range" bracket. The trajectories of up to ten tracers are presented at one time. A firing rate of ten tracers per second is used and a total of 100 tracers is provided each airplane. Both the aiming error in feet at the time each tracer leaves the firing airplane and the minimum pass distance of each tracer as it passes the target airplane are recorded.

Rear-view mirror and synthetic display

During air-to-air combat simulation, the only condition under which both pilots can see each other simultaneously

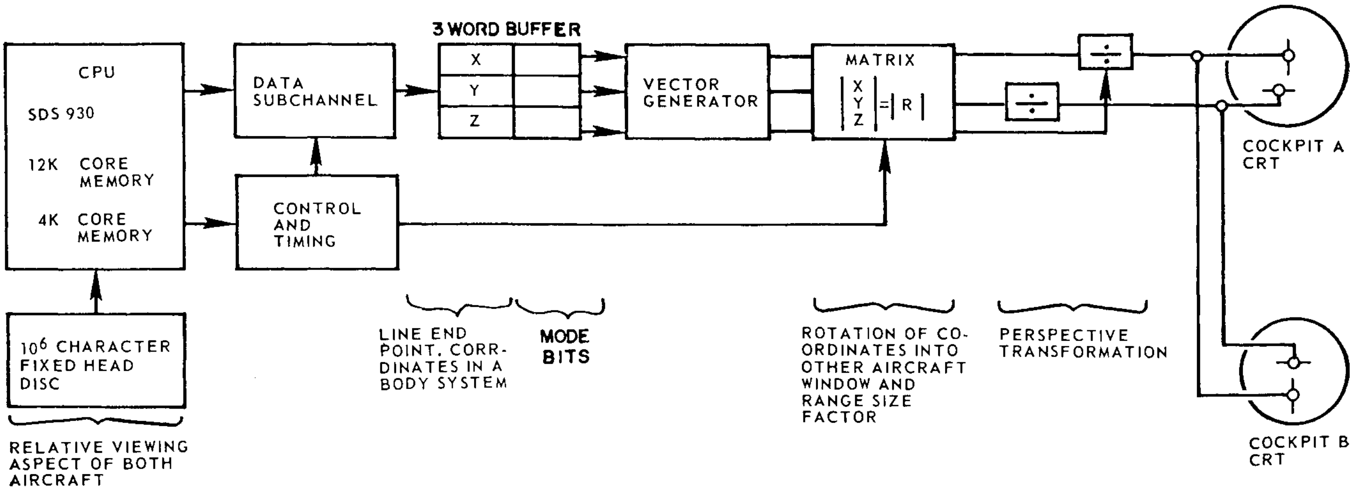

Fig. 10 Time-shared views into processing.

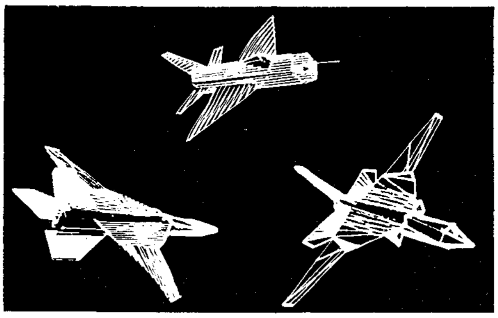

Fig. 11 Aircraft images.

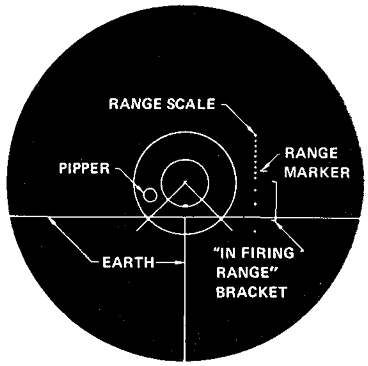

Fig. 13 Gunsight.

in their forward 80° scenes, is when they have near head-on trajectories. Under other conditions, either one or both pilots would not see the other airplane in the forward scene. Two unique visual aids have been provided to overcome this limitation, a rear-view mirror and a synthetic display.

The first air is accomplished by simply transposing the visual system scene to a mirror image of the real situation when the opposing airplane is within an 80° aft cone. Thus, when one airplane leads the other, the pilot in that cockpit sees the chasing airplane in his visual system as though viewing it in a large rear view mirror. The gunsight is not displayed when the visual system is acting as a mirror.

When the opponent is in neither the forward nor the aft 80° vision cone, the second aid is brought into play. This is the "radar-like" synthetic display that appears on the screen below the gunsight rings. Four example situations are illustrated on Fig. 14. The synthetic display indicates the position of the opposing airplane relative to its own airplane's body axes. The "hand" points the direction of the adversary in the clock-centered coordinate system, while the small circle indicates whether he is above, below, or in the display's own airplane X-Y plane. The dot on the large scale also indicates the direction the hand is pointing to aid in interpretation when the hand is short. The length of the hand represents the X-Y plane component of the separation distance between airplanes and the distance between the small circle and the end of the hand represents the Z component of the separation distance. Both distances are represented on the same scale. The scale is approximately proportional to the square root of the distance and gives better sensitivity at close ranges than would a linear scale. This scale was selected to approximate the normal degradation of range acuity that occurs with increasing range.

Space coordinate transformations

The equations of motion for all aircraft involved in the simulation are solved in the CPU, yielding point mass position information in an earth-fixed coordinate system, and earth relative vehicle body attitudes in 9-element direction cosine matrix form. A yaw-pitch-roll rotational sequence is used. These 6-degree-of-freedom independent coordinates for each vehicle are available in real time updated at 20 times per second.

The method of integration of direction cosine rates was selected over an Euler angle method because of the desired full maneuvering freedom of each vehicle without "gimbal lock" anomalies. An execution of a program for the matrix updating from vehicle body rate inputs, including normalization and orthogonalization to maintain a true direction cosine set, is less of a burden on the CPU than the same function performed in a "lockless" redundant gimbal formulation. The resulting attitude matrix is also much easier to use in forming the various transformations (e.g., body to earth, body to body, etc.) than an equivalent Euler angle set would be. An implementation in the CPU software of the basic matrix operations (multiplication inversion, vector multiply, etc.) provides to the programer most of the tools needed for geometric calculations. Euler angle sets as required for display devices or equipment simulation which have gimbal form (attitude balls, platforms, radar gimbals, etc.) are readily formed from the direction cosine terms.

The high information density image readout device outputs synchronized deflection and video signals defining the aircraft B as expressed in its own body-fixed orthogonal coordinate system. Transformation of deflection signals representing aircraft B as seen from aircraft A are performed with the matrix operator, as shown in Fig. 10. The relative geometry is shown on Fig. 15. The coordinate systems X_A, Y_A, and Z_A and X_B, Y_B, and Z_B are fixed in the bodies of aircraft A and B, respectively, System E is earth-fixed, $\boldsymbol{\rho}_P$ is the body fixed vector defining visual system node point (the pilot eye point) in aircraft body axis system, $\boldsymbol{\rho}_C$ is the range vector $(\mathbf{V}_A - \mathbf{V}_B)$ expressed in the E coordinate system, $\boldsymbol{\rho}_F$ is the "describing" vector of solid aircraft body B; the 3 analog signals provided by the aircraft Image Readout device are the components of $\boldsymbol{\rho}_F$ expressed in coordinate system B, and $\boldsymbol{\rho}_{LOS}$ defines the direction the describing point O_{BF} lies from O_P, and is the sought vector quantity for synchronized display in the aircraft A coordinate system.

Airframe Characteristics Representation

Representation of the airframe equations and their characteristics over the Mach number altitude flight envelope is an example of using simplifying assumptions to minimize computation time. In the initial mechanization, primary emphasis has been placed on good representation of the airplane performance characteristics. The longitudinal characteristic equation is a quartic. A first-order roll representation is used. Sideslip equations are omitted, hence the rudder pedals are not effective. No attempt has been made

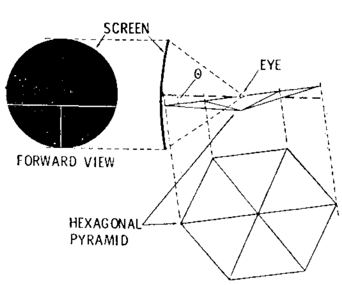

Fig. 12 Earth representation.

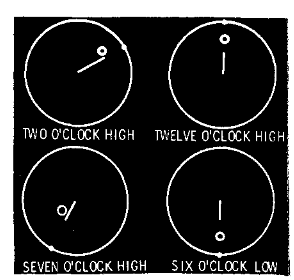

Fig. 14 Synthetic display.

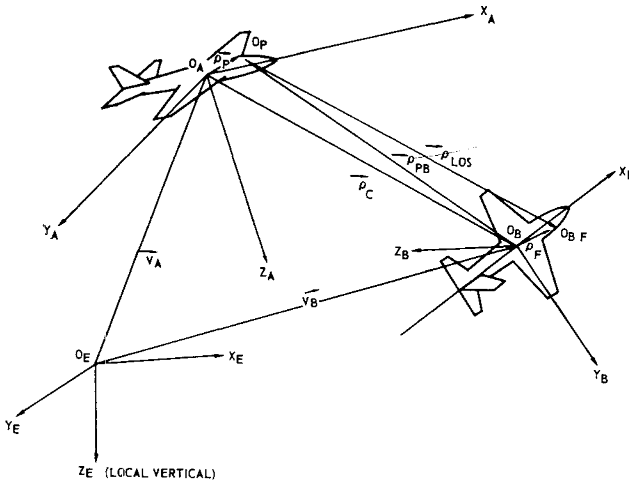

Fig. 15 Aircraft relative geometry.

to simulate inner loops for control systems or stability augmentation systems. An update rate of greater than 20 times per second would be needed for some inner loops. Flying qualities representative of desired or known flight characteristics, throughout the flight envelope, are achieved by adjusting stability derivatives and by applying appropriate slopes and limits to generated functions.

Equations of Motion

The simplified total equations of motion in body axes are:

$$\dot{w} = qu + g\cos\theta\cos\phi - g/W(L_B + T\sin\epsilon_T) \quad (1)$$

$$\dot{u} = -qw - g\sin\theta + g/W(T\cos\epsilon_T - D_B) \quad (2)$$

$$\dot{q} = \mathfrak{M}/I_y \quad (3)$$

$$\dot{p} = \mathfrak{L}/I_x \quad (4)$$

$$r = (pw + g\cos\theta\sin\phi/u)$$

$$w = \int\dot{w}dt + w_0, \qquad u = \int\dot{u}dt + u_0, \quad (5)$$

$$q = \int\dot{q}dt, \qquad p = \int\dot{p}dt$$

The first two equations are the linear accelerations along the Z and X body reference axes, respectively. The next two equations are the angular pitch and roll accelerations about the Y and X axes. The fifth equation is the angular yawing velocity about the Z axis. It is employed to produce the desirable effect of rolling the airplane about the resultant relative wind vector rather than about the body X axis and it provides proper rate of change of heading angle when constant altitude turns are made.

Aerodynamic data

The speed of sound and density ratio are closely approximated by polynomials in altitude. Appropriate aerodynamic coefficients and derivatives are stored in the computer as functions of Mach number, true airspeed, altitude, wing sweep position, lift coefficient, and control positions. Linear interpolation is used between stored points.

Thrust

Military Rated and Combat Rated installed thrust are stored as tables with altitude and Mach number variations represented. Linear interpolation is used between stored points. Variation in throttle position modulates either the Military Rated or the Combat Rated thrust, depending upon whether or not afterburner has been selected. Minimum afterburner throttle stops are provided. Approximate fuel flow is obtained by multiplying thrust by the average specific fuel consumption factor that is consistent with the throttle position.

Buffet and limit lift coefficient

The lift coefficient corresponding to buffet onset and limit lift coefficient are stored in the computer as functions of Mach number and sweep position. When the buffet onset C_L is exceeded, a 10 cycle per second square wave signal is fed to the parallel trim actuator to produce a longitudinal stick shake. The amplitude of the signal is varied linearly from minimum at onset C_L to maximum at limit C_L. Since the stick motion is reflected in the airframe equations of motion, a slight "jiggling" of the visual display also is produced.

III. Checkout and Qualitative Results

System checkout has shown that the loop response with a computation cycle rate of 20 times per second is adequate to provide good representation of two-airplane aerial maneuvers within the high relative velocity region of visual gun-type air combat including head-on passes. Initial airplane characteristics simulated were those of the F-8 Crusader. This airplane was chosen for system checkout because of the detailed data available on actual performance and flying qualities, and familiarity of LTV Aerospace Corporation pilots with the aircraft. Airframe checkout gave satisfactory representation of the F-8 airplane characteristics within the constraints of the simplified equations used. Additionally, TA-4F and F4-J characteristics were simulated and good agreement with flight-test data was obtained.

Since the simulator was conceived primarily as a design tool, and the purpose of the prototype configuration was to demonstrate feasibility of the approach, such stimuli as motion and audio cues were not provided. During checkout, it became apparent that a buffet cue was needed so the stick shaker, described previously, was added. Although this helped considerably, the pilots are accustomed to maneuvering the real airplane in buffet and have a tendency to over-rotate the simulated airplane. To prevent over-rotation as well as add realism the following visual cues are employed: 1) a yaw oscillation as stall warning and 2) a hard wing drop as a final stall indication. Longitudinal stick force gives a load-factor cue to pilots who do not trim it out; however, most pilots do trim continually and thus lose this cue. Without a load factor cue, frequent monitoring of the accelerometer is required at high airspeed to prevent exceeding structural limitations. An effective load-factor cue was achieved by supplying air pressure in proportion to load factor to inflatable g-suits worn by the simulator pilots.

The general reaction to the simulator by pilots has been enthusiastic. They are generally pleased with the perspective view this visual system gives them of the other airplane and the maneuvering freedom they are given throughout their airplane's flight envelope. They require a short training period to adapt to the synthetic display and rear-view mirror presentations and to the incomplete motion and audio cues. Experience and the training required for each pilot to become proficient has not as yet been correlated. It has been observed that experienced fighter pilots who have an engineering background adapt readily to the system and are able to execute aerial combat maneuvers such as the tight turn, roll reversal, barrel roll, split S, loop, and scissors in a proficient manner while either pursuing or evading their opponent. Pilots without engineering background have not been evaluated; however, some engineers without pilot background have performed well.

IV. Experiments

In addition to comparative evaluations of certain existing airplanes, among the first of planned experiments was the systematic investigation of the influence of various aircraft design parameters on air combat success as a gun-fighter. The objective of this experiment was to demonstrate that statistically useful results could be obtained for use in aircraft design programs. The influence of certain aircraft parameters on combat success has been studied by other investigators by the use of computer modeling techniques. In general, in such methods, the airplane is instantaneously rotated to whatever bank angle and normal load factor is desired without regard for airplane dynamics. The pilot is represented by a relatively simple logic statement. The unique features of this simulation approach are the inclusion of airplane dynamics and the integration of the human operators into the loop with their judgment, initiative, and limitations.

Airplane Design Parameters

The expression for energy maneuverability in terms of specific excess power P_s is

$$P_s = (T - D/V)V \text{ fps} \tag{6}$$

Substituting airplane design parameters in the expression yields:

$$P_s = [T/W - (C_{D_0}S/W)q - (n_z^2/q)(1/\pi \mathit{Æ} e)(W/S)]V \tag{7}$$

The principal airplane parameters within the control of the designer are the thrust-to-weight ratio T/W the wing loading W/S and the aspect ratio $\mathit{Æ}$. For airplanes with a similar mission requirement C_{D_0} and e are largely dependent on the choices made for the first three parameters as well as dependent on wing sweep angle and airfoil section. Additional parameters that do not appear in the specific excess power expression are the lift coefficient for buffet onset $C_{L_{\text{buf}}}$ the maximum usable lift coefficient, $C_{L_{lim}}$, and the combat fuel allowance. The first three parameters T/W, W/S, and $\mathit{Æ}$, as well as $C_{L_{\text{buf}}}$ and $C_{L_{lim}}$ were given the greatest attention.

Experiment Conditions

The threat airplane characteristics remained fixed for the experiment. The parametric airplane characteristics were systematically changed after a series of runs. Experienced jet fighter pilots manned the cockpit and alternately flew the threat airplane and the parametric airplane. At the beginning of an experimental encounter, each pilot was aware of the presence and location of the other airplane. During a run, whenever the separation distance exceeded 8 naut miles, the airplane images and synthetic display were turned off to simulate loss of visual contact. Various initial head and tail aspect angles relative to each airplane were tried at altitudes of 10,000 and 35,000 ft. For the parametric evaluation, one set of initial conditions was chosen—2 naut miles abeam of each other on opposite headings with both airplanes at 10,000 ft at a Mach number of 0.90. Each pilot was given a firing time allowance of 10 sec (100 tracers). Pilots attacked and evaded each other in a conventional manner, firing their guns when within the gun firing envelope and when satisfied with their tracking. The problem was terminated and scored when either pilot had expended his supply of ammunition or when six minutes of combat time had elapsed.

Recording and Scoring

Recording is accomplished on a large X-Y horizontal situation plotter, three six-channel strip recorders, and on magnetic tape. At the termination of a data-taking run, the data stored on the tape are automatically read and an off-line program analyzes the results and prints out a summary of each airplane and pilot's performance on the line printer. The printout includes computer organized frequency distribution plots of rounds fired vs aiming error, bullet miss distance relative to the target airplane center of gravity, and firing range. Also plotted are bullet miss distance vs firing range for each airplane.

A tabulated summary is printed for each airplane that includes run time, fuel used, time other airplane is within the forward field-of-view, time within forward field-of-view and less than 3000 ft, time within forward field-of-view and less than 10,000 ft, times other airplane escapes from the forward field-of-view, and time the other airplane is in the rear hemisphere. Minimum, maximum, and mean summaries are given under certain specified conditions, such as during firing, of such things as load factor, lift coefficient, energy maneuverability, aspect angle, separation distance, tracking error, bullet miss distance, burst time, altitude, and Mach number.

Statistical analyses of the recorded data are made to evaluate the relative probability of air combat success of one configuration against another and to correlate the effects of variations in aircraft design parameters on air combat success.

Results

Because of their security classification, the results of the parametric study are not presented. Significant and consistent improvement in the win/loss ratio was obtained by reducing the wing loading, increasing $C_{L_{\max}}$ or increasing the thrust loading. These trends are obvious; however, the experiment established the degree of improvement.

V. Future Developments

Since the concept has been proven and useful data are being obtained with the simulator in its present configuration, the simulator will be developed to improve its capabilities. The first development will be to eliminate the rear view mirror and synthetic displays by providing a more realistic presentation through the use of an increased field-of-view. Each cockpit and its visual system will be enclosed in a sphere and the opposing airplane's position will be displayed inside the sphere. The pilot will have to swivel his head to search for his opponent and his field-of-view will be limited only by airplane cockpit structure. Various means of accomplishing this development are being considered. These include multiple visual systems, gimballed projectors and gimballed mirrors.

Further development will provide improved earth representation, other fire control and radar representations, and increased sophistication of the airframe representation to include the sideslip equations and inner augmentation loops when desired. Additional computer capacity will be required to implement the planned development.

VI. Conclusions

A simulation program utilizing a unique method of presenting visual information to pilots has been initiated using prototype equipment. The purpose of the program is to prove feasibility of dual cockpit simulation and application of the approach to investigations of design parameters on aircraft effectiveness in air combat maneuvers. Conclusions that may be drawn to date are: 1) technical limitations of excessive computation time have been overcome by careful design of the various mathematical representations that comprise the system and use of efficient machine language computer routines; 2) the impression created in the visual system is sufficiently real to permit use of normal piloting techniques; 3) experienced fighter pilots with an engineering background can obtain proficiency in the simulator with a reasonable period of familiarization; 4) the effectiveness of the simulator in evaluating airplane design parameter contributions to air combat success has been demonstrated.