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21

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I. SOME BASIC PROBLEMS IN DESIGNING AIR-TO-AIR FIGHTER SYSTEMS

Like any other aircraft, an air-to-air fighter is the result of a series of design compromises. The design features that typically are involved in the compromises on fighters, however, are peculiar to this type of aircraft. For most military and commercial aircraft the design compromises tend to be made between range and payload, once the general characteristics of the design have been specified to meet the mission requirements. For air-to-air fighters, the most significant compromises tend to be between range, on the one hand, and a set of design and performance factors, on the other, that may be grouped under the term "system agility."

We will use "agility" as a catch-all term referring to the combination of high acceleration, high maneuverability, large sensor coverage and weapon-launch envelopes, and short response time needed by a fighter engaged in combat with a strenuously maneuvering opponent. "System agility" refers to the agility of the aircraft in combination with its sensors and ordnance, not just to airplane performance alone.

Two of the principal design parameters tending toward high agility for the aircraft are low wing loading and high thrust-to-weight ratio. In both cases, the demands are for performance in excess of the requirements imposed by takeoff and landing conditions or by per-

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formance in non-maneuvering flight. There are direct penalties in range associated with the weight and drag of a low-wing-loading configuration and with the weight, drag, and preferred engine cycle for high thrust-to-weight ratio. A high degree of agility for the sensor and ordnance portions of the fighter system also tends to add weight and drag to the system. For example the pilot of an air-to-air fighter needs excellent visibility in the rear quadrants. A canopy providing this kind of viewing will have considerably more drag, especially in supersonic flight, than a faired-in canopy with restricted rearward visibility. Similarly, increasing the firing envelope for air-to-air weapons may add weight and/or drag with attendant range penalties.

Our references to range penalties, so far have been in the sense that range suffers if agility increases and all other factors remain constant. Other factors need not remain constant, of course. If total system weight may be varied freely, agility may be increased while range is held constant. Unfortunately, though, there is nothing free about increases in system weight. An increase of one pound in subsystem weight (to provide, say, added ordnance system capability) will result in anywhere from 4 to 10 pounds total weight increase in the system, depending on the particular performance level of the design aircraft, if airframe agility and range are held constant. System costs increase with weight* and the trade between performance and added airplane size becomes increasingly expensive at the higher performance levels, so that there are practical limits to this form of design compromise. Not only can the system cost increase exponentially with added performance, but the size of the airplane can become too great for practical use as a fighter because of increasing detectability, vulnerability, and other operational considerations.

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*For example, 10 percent increase in gross weight for a supersonic fighter design in the 40,000 lb size weight could result in about a 7 to 8 percent increase in flyaway cost.

II. THE SIGNIFICANCE OF DESIGN REQUIREMENTS FOR CLOSE-IN FIGHTER-VERSUS-FIGHTER COMBAT

If the combat task of a fighter aircraft consisted only of launching weapons against non-maneuvering targets, and if launches could always be made at fairly long range from the target--say, beyond visual identification or visual detection ranges--the design problem would be considerably simplified. Aerial combat at long range implies reliance on ground-based sensor and control systems and/or on use of airborne radar for acquisition, tracking, and fire control. Cockpit visibility requirements for such operations are dictated primarily by takeoff and landing performance. Maneuver load factors for conventional attack modes vary inversely with the range to the target, so that long-range attack is less demanding on aircraft turning performance. Likewise, if the target is not maneuvering--a more likely condition for long-range combat than for close-in combat--the agility required in aircraft and ordnance performance is low compared to that required for combat with a maneuvering opponent.

A design mission requiring that a fighter system have superior performance in close-in maneuvering combat (i.e., combat within visual detection and identification range) places the most demanding requirements on fighter system agility. Because it requires less energy to accelerate a small object than a large one, one design approach might be to provide a great deal of agility in the ordnance and fire-control subsystems, to compensate for lack of agility in the aircraft. This approach could be useful to a degree, but it is clear that ordnance agility cannot compensate for lack of aircraft agility in situations where the aircraft is on the defensive and must maneuver to evade the enemy's attack. Nor will ordnance agility, in many situations, compensate for lack of aircraft agility to close on an enemy in order to press an attack. The result is that ordnance agility should be considered as a highly desirable supplement to the aircraft's performance, rather than a substitute.

A fighter that must be capable of both long-range combat and close-in combat will be designed, in part, on the basis of requirements for the long-range task. For example, the frontal area and the distribution of equipment in the nose section are likely to be dominated by the requirements for the air-intercept radar, and the load of long-range missiles will influence considerations of weight and stowage for other items of payload. But satisfying the requirements for the close-in combat task will dominate many features of the design and will provide the most difficult problems in design compromise.

III. COMPLEXITY OF THE DESIGN PROBLEM AND SOME AIDS TO THE ANALYST

Suppose that a decision has been made to design a fighter capable of both long-range and close-in air combat, and that the task of the analyst is to determine the desired combination of aircraft and ordnance characteristics. The role of the analyst in this case, working with the aircraft design team on the one hand and the decisionmakers on the other, is to evaluate the performance of selected system and subsystem designs in terms of criteria established by the decisionmaker. The analyst should be able to demonstrate to the latter not only the relative performance in the combat role of alternative designs but the sensitivity of the performance to changes in major system parameters. In this process the analyst becomes influential in the selection of criteria as well as in their application.

Because of the special problems associated with the close-in air combat task, we will focus on the portion of the analysis related to that task. The analyst is faced with problems like the following: What are the parameters of such combat? That is, what values of altitude, airspeed, load factor, range, range rate, angles, and angle rates are typical of such aerial duels? What are the quantitative results of changes in individual design features on the overall performance of the system? What is the expected outcome of combat, under various opening conditions, between an aircraft of a particular design and a given opposing fighter? The list of such questions could be extended, but it is clear already that the answers involve a large number of variables, and that some of the major determinants of the problem are extremely difficult to quantify.

The three factors that determine the outcome of any fighter duel are the opening conditions, the skills and tactics of the opposing pilots (or teams, in the case of combat involving more than one versus one), and the fighter system performance. The designer and the analyst can work only with the last of these three, and that may be, on the average, the least important if the opposing aircraft are of the same design generation.

The analyst's problem may not be completely unsolvable (though at times it appears to be so). There are a number of analytical aids and procedures that he can exploit, each offering somewhat different capabilities and limitations.

Three methods of particular interest to the analyst working on the close-in combat problem are computerized design studies, computer simulations and certain types of flight tests. Computerized design studies make it possible to generate, in outline form, designs for sizeable families of hypothetical aircraft, with parametric variation of interesting performance and/or structural features.* These techniques can be used to produce plots of variation in such performance factors as range or energy-maneuverability (EM) characteristics[(4)] as functions of such design variables as thrust, engine bypass ratio, wing geometry, etc.

If EM characteristics are used as indication of agility for close-in combat, one can perform a variety of design tradeoff studies using the computerized design approach. Such studies are extremely valuable, but the selection of EM values for use as criteria is not completely satisfactory. Some problems are that the degree of superiority in combat of design over another is not revealed by the relative EM values nor is the preferred allocation between thrust loading and wing loading shown directly. The selection of points in the flight envelope to use for criteria (one may choose to use the EM value for any one or any number of combinations of airspeed, altitude, and load factor) has to be done on the basis of expert opinion. Thus it is useful to supplement this type of analysis with some more direct inspections of the close-in combat situation.

Digital simulation can be used to portray, both numerically and graphically, the flight paths of fighters in close-in combat. The simulation can be done at any degree of realism with respect to airplane performance and air combat tactics from two-body two-dimensional

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*Computer programs for design study are in widespread use in the aircraft industry and in government research and development organizations. References 1 and 2 are early examples of these techniques. Reference 3 is a recent example.

maneuvers described purely geometrically (e.g., constant-velocity, constant-g maneuvers without regard to actual aerodynamic and propulsion performance) up to three-body, three-dimensional, six-degree-of-freedom simulation including detailed aerodynamic and propulsion performance and fairly realistic tactics. The simpler simulations, of course, can provide only partial answers, but can be quite useful in determining trends and in selecting problems for detailed examination via more complex techniques. The more complex simulations can produce detailed time histories of the parameters of air duels of interest to the designer, such as the time histories of altitude, g-loading, etc., mentioned earlier as descriptors of the combat. We will return in the last section of this paper to a description of such a model developed at RAND.

Another variety of simulation deserves separate comment: simulations with one or two pilots in the loop. Man-in-the-loop simulations are under development and test in several projects.[5,6] The mechanism for these simulations typically consists of two fighter cockpit mock-ups, each with a display screen upon which the image of the opposing fighter can be continuously projected in the proper position and perspective to indicate range and angle off. Each pilot "flies" his airplane against the other in maneuvering combat, the paths of the two aircraft being calculated by a computer linking the two cockpits and displays. In addition to their obvious potential as training devices, man-in-the-loop simulators will offer valuable capabilities to the design analyst. Flight tactics can be more realistic and versatile than in the pure computer simulations. For man-in-the-loop simulations to be most useful, it will be important to provide full flight data recording, printout, and playback features, both to provide information to the analyst and to permit experimental control between runs representing different aircraft designs.

The third type of aid to the designer and analyst mentioned above is flight tests. Although there are not many controlled flight tests with instrumentation and data recording adequate for the analytical study of air combat, such tests are occasionally performed. An example is the Combat Hassle series conducted in 1967 at the Air Proving Ground

Center. The test objectives were oriented toward a specific problem in air combat which need not be described here. The relevant point is that a series of simulated dogfights were flown over an instrumented range, permitting detailed observation of significant parameters of the combat.

Data routinely prepared to record the sorties included fairly exhaustive tabular data describing the flights plus traces of the aircraft flight paths on the XZ, XY, and YZ planes, and plots versus time of g-loading, aircraft separation distance, track crossing angle, angle off, lead angle, and Mach number. These data constitute an invaluable library of information on physical aspects of close-in air combat.

The following two figures illustrate the kind of graphical data obtainable from these records. Figure 1 is a plot of g-loading versus time for an airplane in one of the Combat Hassle sorties. Figure 2 is a plot of Mach number versus time for both aircraft on the same sortie.* Later we will look at a representative set of aircraft flight paths from a Combat Hassle run, in three dimensions.

The advantages of controlled and instrumented flight testing are the greater completeness and greater realism of the tests as compared with simulation, especially with regard to tactics. Disadvantages are the high cost and long time required for flight tests, and the relative difficulty of experimental control. Despite these drawbacks, some amount of flight testing is highly desirable as a check on the adequacy of simulation techniques.

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*Data provided by Colonel Warren T. Whitmire, Air Proving Ground Center.

PLOT OF G's vs TIME FOR A FIGHTER IN A COMBAT HASSLE SORTIE

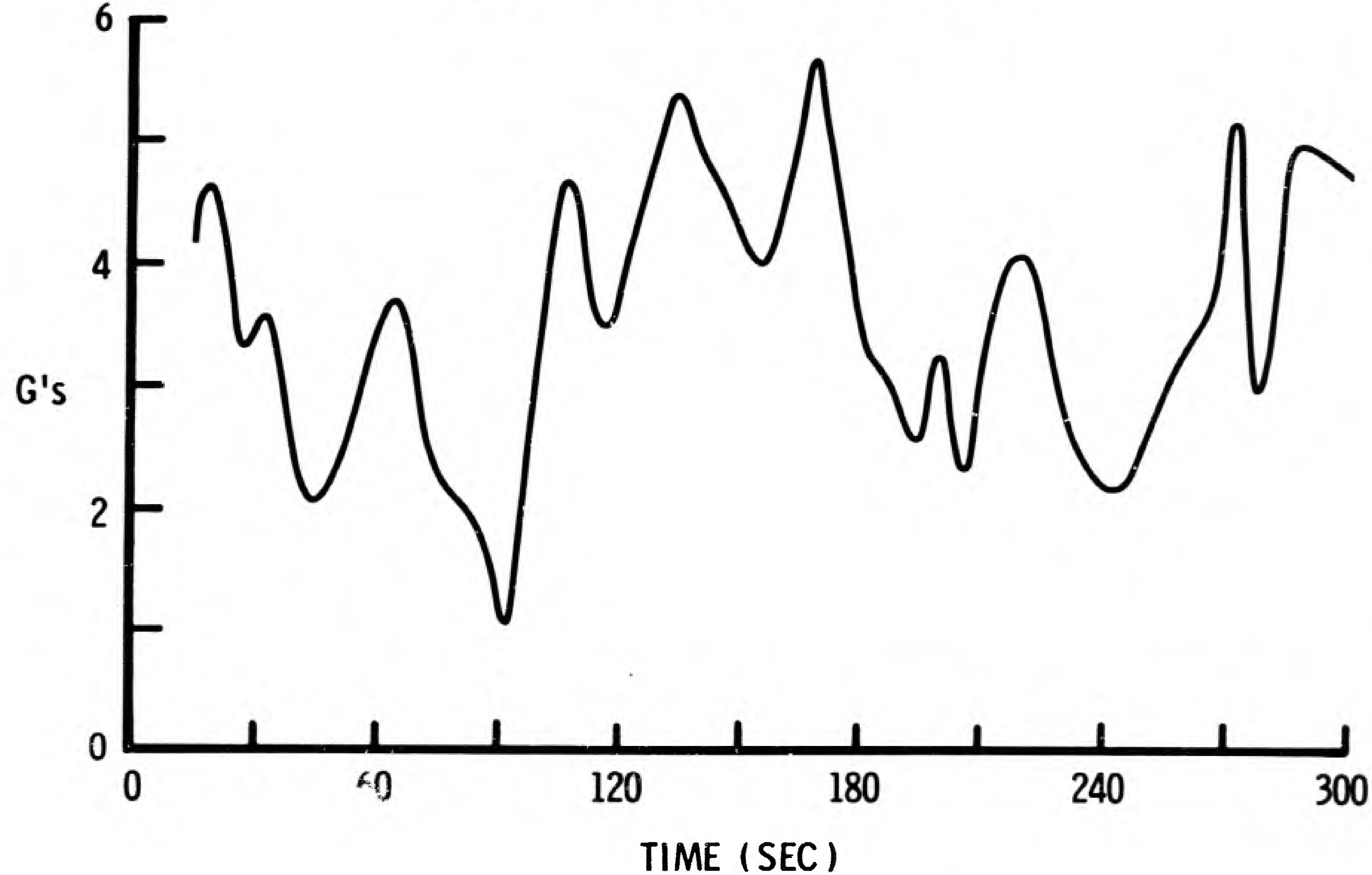

Fig. 1

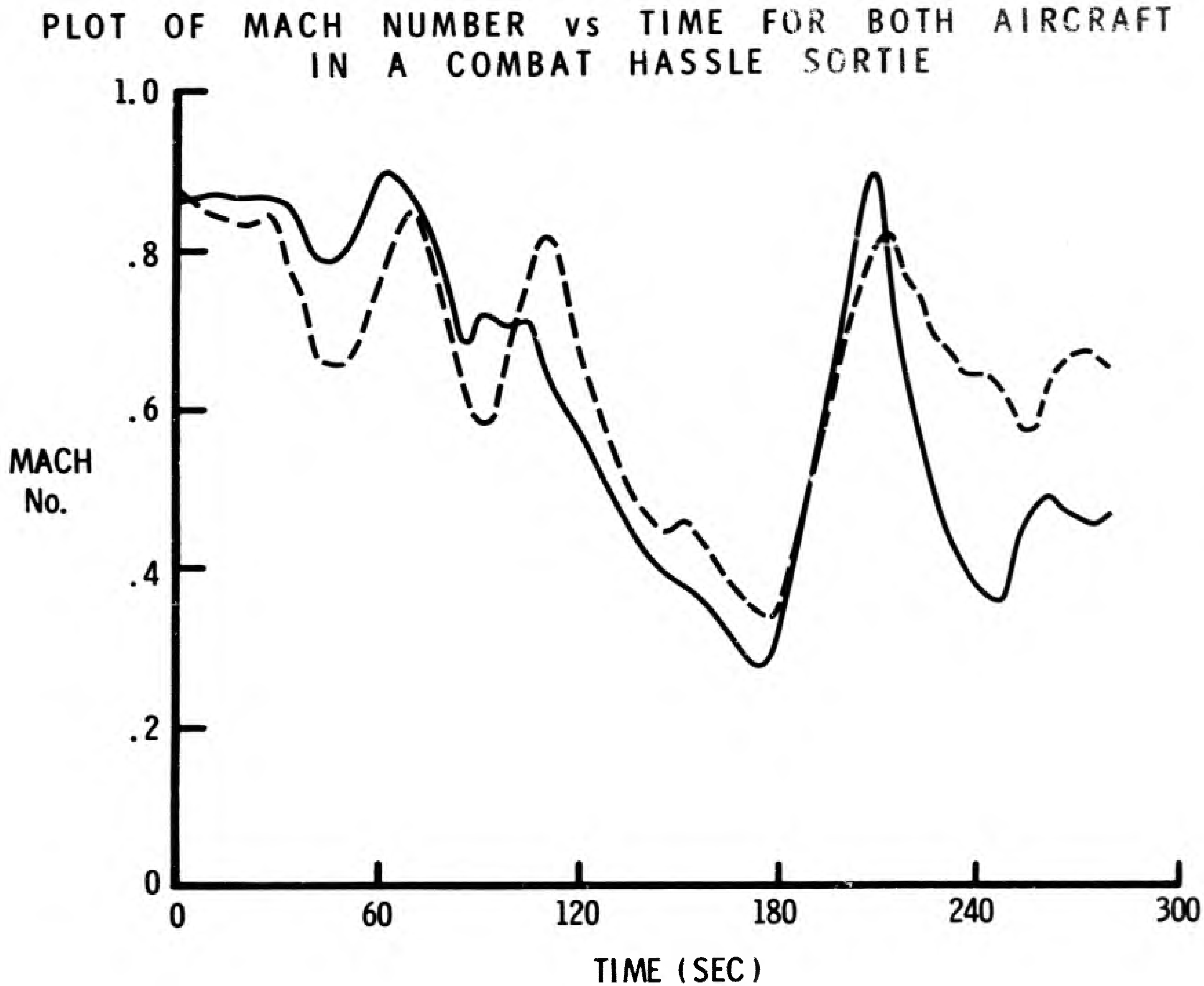
PLOT OF MACH NUMBER vs TIME FOR BOTH AIRCRAFT
IN A COMBAT HASSLE SORTIE
1.0
.8
.6
.4
.2
0
MACH
No.
0
60
120
180
240
300
TIME (SEC)

Fig. 2

IV. RAND TECHNIQUES IN SIMULATION AND DISPLAY OF AIR COMBAT

The digital computer simulation model in use at RAND for analysis of air combat systems, called the TACTICS model, was programmed under the supervision of J. H. Hutcheson.[7] As described in an earlier paper by the present authors,[8] this is one of the more complete computer models currently available for dynamic simulation of maneuvering flight. It is designed for primary use as a research tool in studies of preferred air combat system design; for this reason, emphasis in the model is on an analytical description of the processes of air duels rather than on computing expected or probabilistic outcomes.

Aerodynamic and propulsion performance of each of three maneuvering bodies is represented for three-dimensional flights and for pitch, roll, and yaw altitudes, giving six-degree-of-freedom motion. Realism for fine scale analysis of flight characteristics is limited in that each body is treated as a point mass.* The flight paths are governed by a guidance policy subroutine, in which the sequence of maneuvers for each body is specified. The maneuvers may be specified for one body independent of the maneuvers of the others, and/or they may be conditioned upon the position and maneuvers of the others.

As a simple example, an air-to-air missile may be given a launch signal when the aircraft carrying it is in a certain position and heading relative to a target. The missile launches after a specified delay, flies through a boost phase without guidance, and then continues with modified propulsion on a heading determined by its guidance law and the position and motion of the target. In another example, an airplane may be instructed to fly a lead-pursuit course against a target until it overshoots (i.e., until it cannot produce enough lift or thrust to perform the commanded acceleration), at which point it is commanded to do a split-S escape maneuver.

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*The model can be used in a variety of applications other than aerial combat simulation and analysis, though it was developed primarily for the uses described here. Other applications include surface-to-air, air-to-surface, and space flight simulations.

The maneuver routines are made up of combinations of standard routines which have been programmed and stored, plus any special instructions needed for a particular family of cases. The standard library of "building block" maneuvers includes such flight routines as pure pursuit, lead pursuit, lag pursuit, proportional navigation, split-S, Immelman, and a variety of horizontal, diving, and climbing turns.

Aircraft and missile performance data can be input in the form of tables or analytical expressions. Performance data for aircraft typically consists of tables of $C_{L(MAX)}$ vs Mach number, C_D vs C_L and Mach, angle of attack vs C_L and Mach number, placard limit speed vs altitude, and thrust and fuel flow vs Mach and altitude for military and afterburner power settings. (Fractional power settings may also be used.) To date missile performance data has been input via analytical expressions, including applicable system time constants.

The output is of two kinds: tabular data and graphical display. The tabular output provides a rather complete analytical description of the combat. Some 40 values of position, velocity, and acceleration, including relative and absolute position and motion data, are typed for each of the three bodies at each print interval, the print interval usually being of the order of 1/2 or 1 second. This printout is the basic source of information to the analyst.

The graphical display may be in any of several forms. It its simplest form, it is a set of 3 projections of the flight paths on orthogonal planes. This type of display, as shown in Fig. 3, is easy and cheap to produce and provides a general picture of the situation to the analyst. However, it is difficult to visualize the three-dimensional motions and the time relations of the paths using this form of display. A stereo display technique has been developed by Harold Petersen and Rein Turn of RAND[9] which permits a single observer to view the flight paths in stereo in real time or any reasonable variation from real time, including instantaneous display of the entire paths. The viewer may select his apparent angular position with respect to the flight paths--that is, he can view the action from above, below, or any side aspect. He also has control over his apparent distance from the action, by zooming the view in or out.

X-Y PROJECTION OF A RAND SIMULATION OF AIR COMBAT FLIGHT PATHS

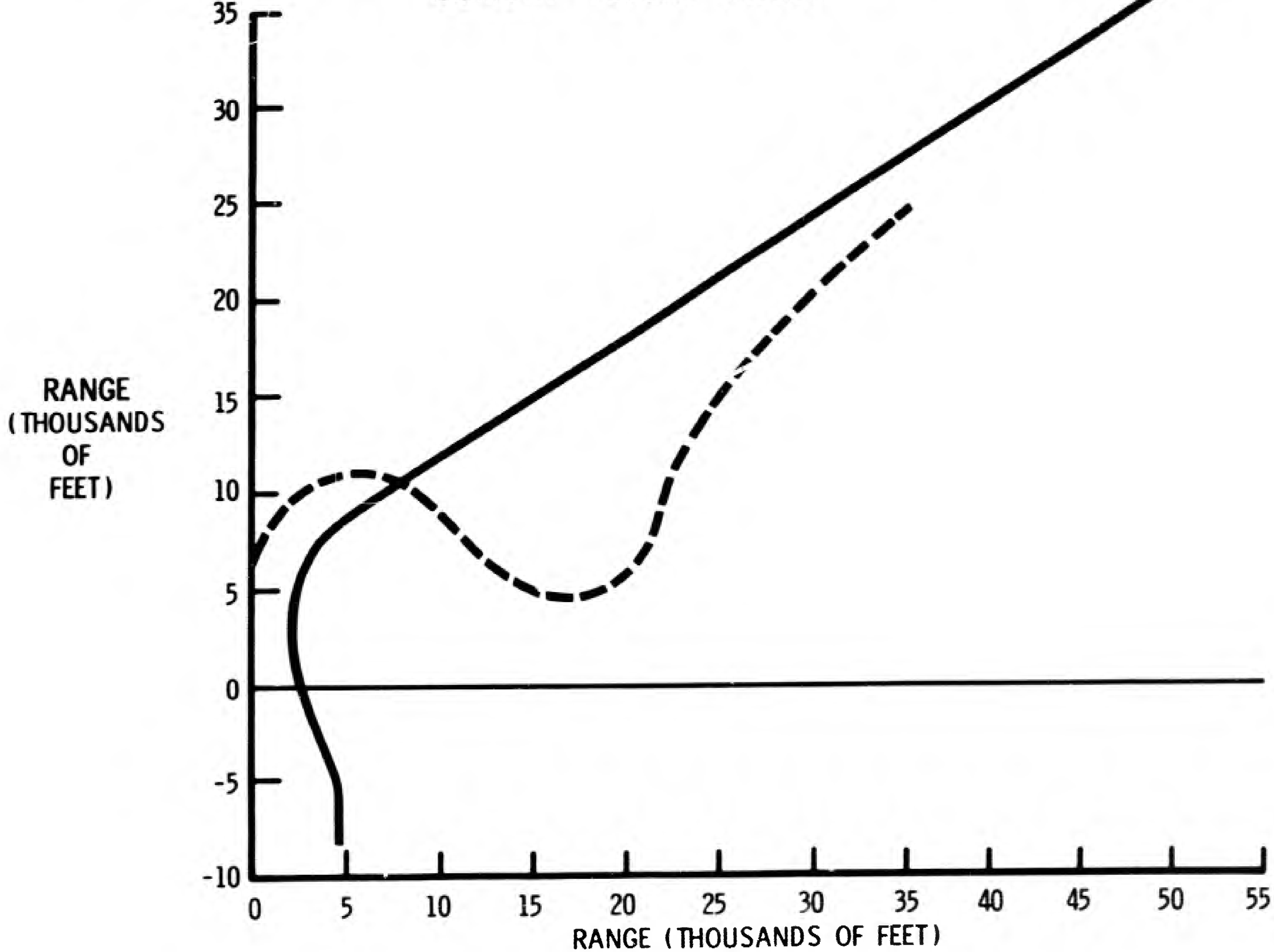

Fig. 3a

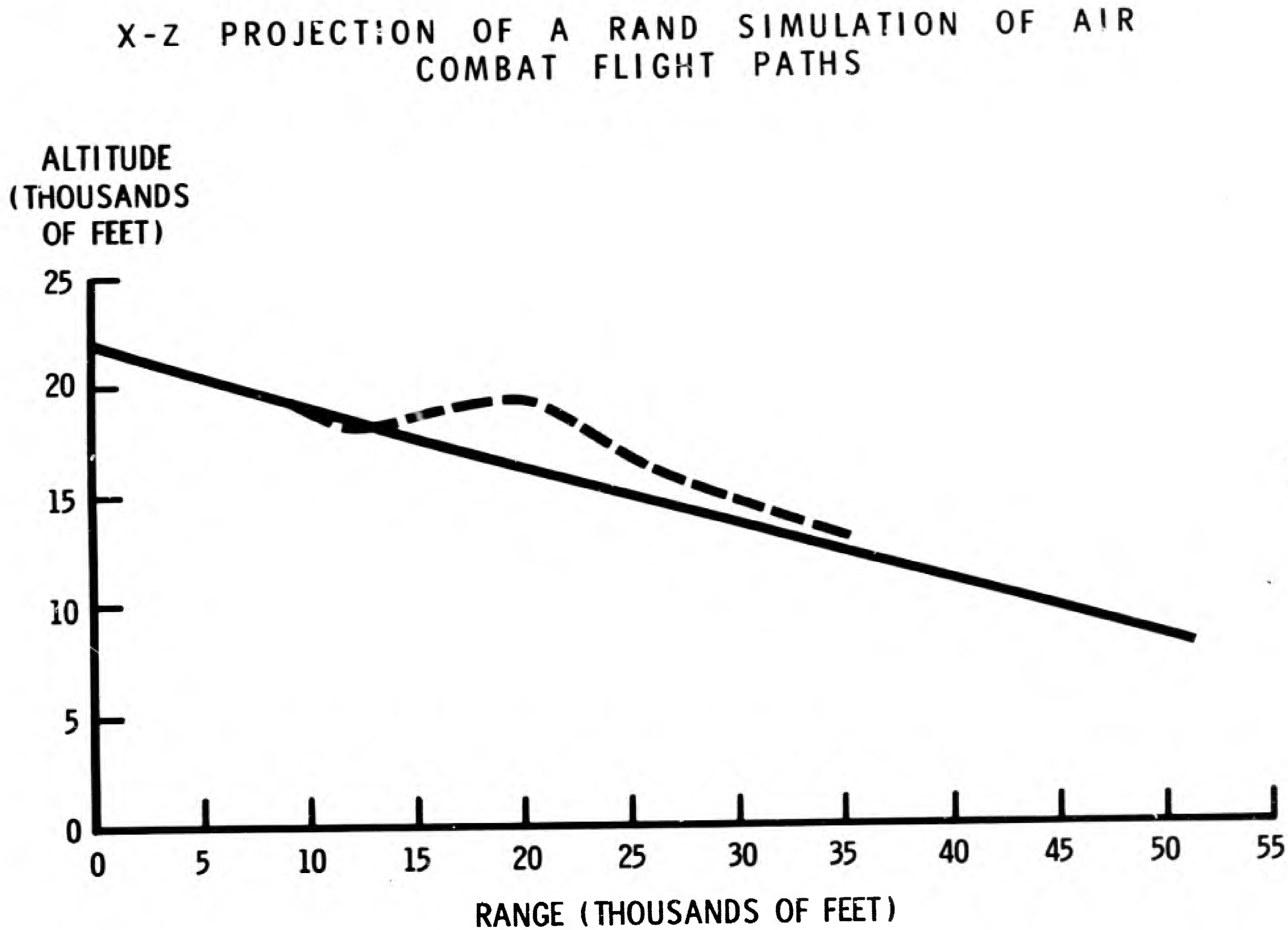
X-Z PROJECTION OF A RAND SIMULATION OF AIR COMBAT FLIGHT PATHS
ALTITUDE (THOUSANDS OF FEET)
25
20
15
10
5
0
0
5
10
15
20
25
30
35
40
45
50
55
RANGE (THOUSANDS OF FEET)

Fig. 3b

Y-Z PROJECTION OF A RAND SIMULATION OF AIR COMBAT FLIGHT PATHS

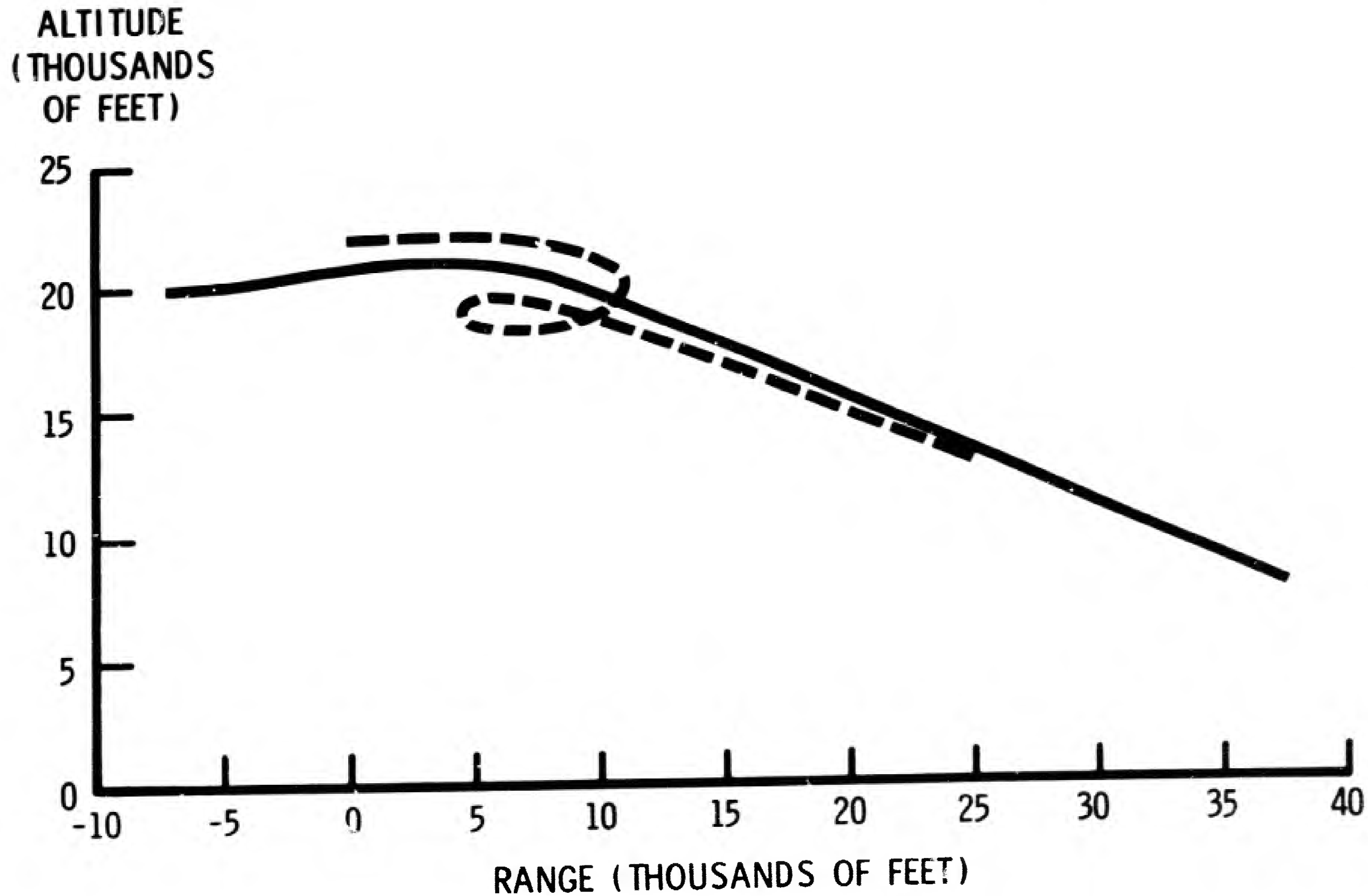

Fig. 3c

The stereo display can be used to reproduce flight paths from any set of data for which x, y, and z coordinates exist as a function of time. RAND has prepared stereo card decks for approximately half of the Combat Hassle sorties, so that these experimental runs can be played back and viewed at will.

A third form of graphical output is still stereo slides or hard copy, as shown in the stereo pairs of Figs. 4 and 5. Figure 4 shows flight paths generated by the RAND simulation model and described in Ref. 8. Figure 5 shows paths actually flown in a Combat Hassle sortie. With appropriate projection equipment, the stereo slides can be shown to group audiences.

The graphical output in any of these forms is useful mainly to help the analyst visualize the combat action that has been simulated (or flown), and to communicate to others what is going on. The tabular output data, though far less spectacular, is more significant for purposes of analysis.

There are several limitations of the RAND methodology.* It is often difficult and always time-consuming to set up and check out a new set of guidance policies for a family of runs. It appears to the authors that being able to use a man in the loop during this part of the process would be advantageous, along with the capability to run without a man in the loop during parametric variations of system performance or tactics. The program runs somewhat slower than real time on the IBM-7044 computer, so that checkout and production are expensive in computer time. Generally, only brief encounters or portions of an encounter are simulated, with simulated engagement times of about one to three minutes. And a fundamental problem in any such simulation exists in the RAND TACTICS model, namely, the problem of representing appropriate and convincingly realistic tactics in a maneuvering air duel.

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*The present discussion applies to the large, 3-dimensional dynamic simulation model. As noted in Ref. 8, RAND also uses a variety of simpler, mainly 2-dimensional models, which are characterized by different limitations and capabilities.

STEREO PAIRS OF 3-D COMPUTER-GENERATED DISPLAY OF A SIMULATED PORTION OF AN AERIAL DUEL

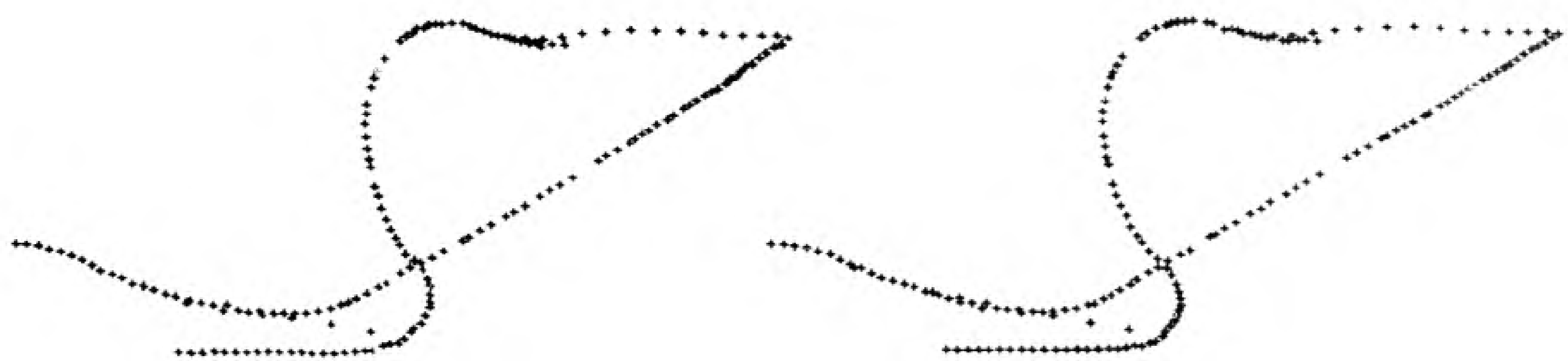

Fig. 4

STEREO PAIRS OF 3-D COMPUTER-GENERATED GRAPHICAL
DISPLAY OF A COMBAT HASSLE SORTIE

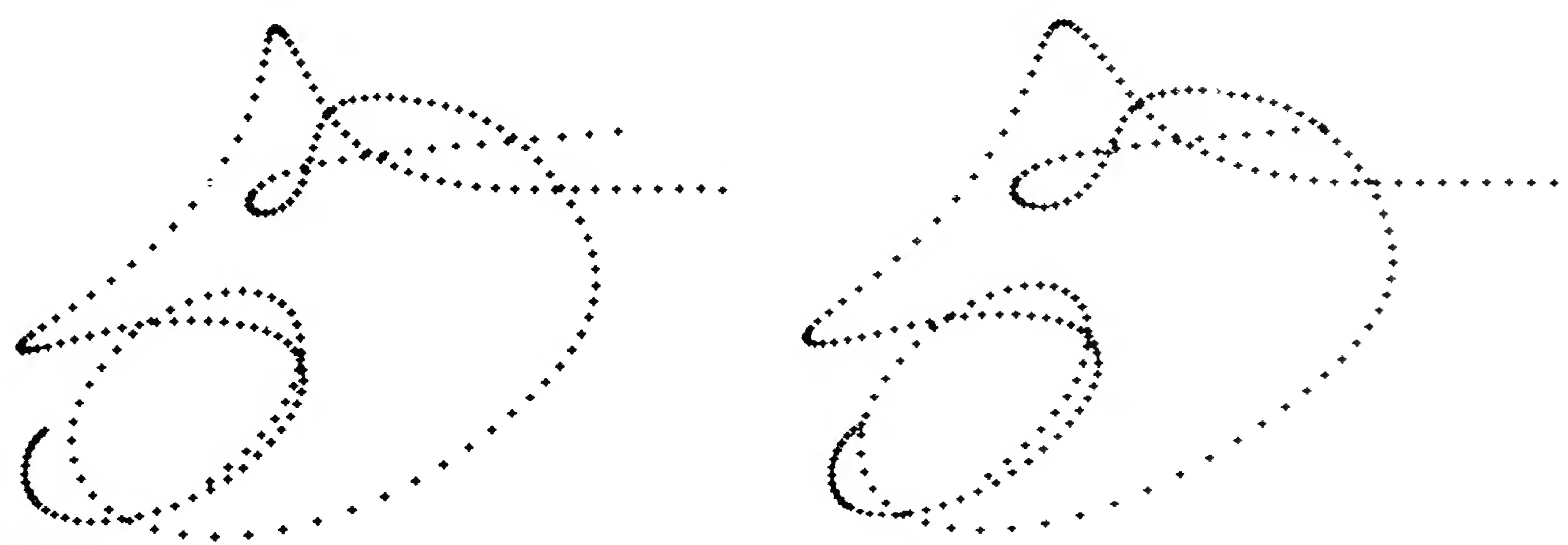

Fig. 5

The capabilities and advantages of the RAND simulation may be stated in terms of experimental control, computational completeness, time, and cost relative to other methods of generating air combat flight paths and observing the outcomes. The simulation is much cheaper and faster to run than actual flight tests and of course provides complete experimental control. It is more complete and accurate than two-dimensional (or other simplified) simulations.

Regarding the limitation mentioned above with respect to tactical realism, the attempt is made to insure that appropriate tactics are programmed via consultation with pilots skilled in the teaching and practice of air combat. Because the simulations generally represent only one or two moves and countermoves by each opponent in a duel, it appears possible to produce credible simulations of these segments of a dogfight. The attempt to preprogram a long series of maneuvers for a protracted dogfight, with the explicit detail necessary for computer input, would certainly pose much greater problems in achieving credibility. As noted earlier, the primary intent of the RAND model is to permit detailed examination of the dynamic processes of air combat, rather than to generate the outcomes of such combat. Thus it is more suitable for close examination of how and why two competing versions of a fighter or missile design differ in their performance, than for computing such numbers as the outcomes or kill probabilities of competing systems over a large number of cases.

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