R-979-PR
July 1972

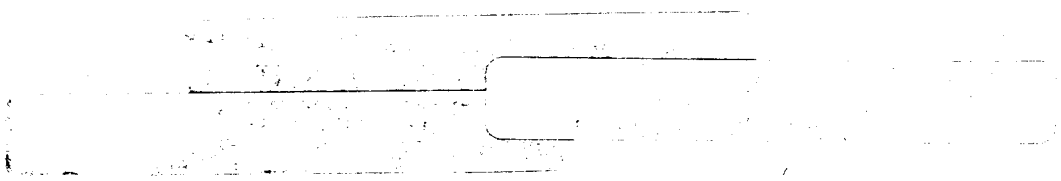
TACTICS II: Maneuver Logic for Computer Simulation of Dogfight Engagements

R. L. Spicer and L. G. Martin

A Report prepared for

UNITED STATES AIR FORCE PROJECT RAND

Rand
SANTA MONICA, CA. 90406



This research is supported by the United States Air Force under Project Rand—Contract No. F44620-67-C-0045—Monitored by the Directorate of Operational Requirements and Development Plans, Deputy Chief of Staff, Research and Development, Hq USAF. Views or conclusions contained in this study should not be interpreted as representing the official opinion or policy of Rand or of the United States Air Force.

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Published by The Rand Corporation

PREFACE

For the past four years, Rand has conducted a variety of studies evaluating the effectiveness of fighter weapon systems in the air combat environment. To conduct these studies, it was necessary to simulate the kinematics of various kinds of aerial encounters--e.g., aircraft versus aircraft, air-to-air missiles, or surface-to-air missiles. In 1969, Rand completed the development of TACTICS, a general-purpose computer model that can simulate the dynamics of flight in three-dimensional space of as many as three vehicles simultaneously.(1) Although TACTICS can simulate many types of air-to-air engagements, it lacks the required logic to realistically simulate close-in dogfights. Inasmuch as a primary concern of the U.S. Air Force is the evaluation of various fighter weapon systems in such encounters, Rand undertook to develop this additional maneuver logic.

This report presents the rationale on which the new maneuver logic for fighter aircraft is based, discusses its incorporation into the TACTICS model (now designated TACTICS II), and shows examples of dogfights generated with this logic that appear sufficiently realistic for analysis and evaluation of fighter weapon systems. It should be useful to analysts in the office of the Assistant Chief of Staff, Studies and Analysis; the Aeronautical Systems Division and the Armament Development and Test Center, Air Force Systems Command; and the Tactical Air Command.

SUMMARY

Rand has developed maneuver logic for fighter aircraft for computer simulation of one-on-one, close-in air combat. The logic is essentially analytical, being based on the fundamental physics of the dogfight situation and the performance capabilities of fighter aircraft.

The objective of this maneuver logic is to require each aircraft to attempt to achieve a weapon (missile or gun) firing opportunity against the other aircraft, primarily within the opponent's rear hemisphere, while denying the opponent any firing opportunities, if possible. The aircraft that can perform faster, tighter turns without losing excessive energy relative to its opponent is most likely to accomplish this goal.

The technique used involves directing each aircraft to fly a pursuit course on some point behind (or to the side) and above or below its opponent. This point, called the *dogfight pursuit point*, is defined by two components: One, the lag increment, directs the fighter aircraft into the opponent's rear hemisphere; the other, the altitude increment, is used to partially control the aircraft's velocity (by causing it to climb or dive) such that the aircraft stays in its high-turn-rate, low-turn-radius speed region. Each aircraft's turn capability, total energy, and energy relative to its opponent are managed by choosing the proper mix of bank angle, load factor, and thrust to prolong the aircraft's capability for high turn rates and small turn radii.

This logic has been incorporated into the Rand TACTICS-II computer model, which can simulate a wide variety of three-dimensional aerial engagements. The model has been used to simulate dogfights under various starting conditions. The results compare favorably with flight test combats and basic U.S. Air Force fighter maneuvers.

CONTENTS

PREFACE iii

SUMMARY v

Section
I. INTRODUCTION 1

II. DOGFIGHT MANEUVER LOGIC 3
Diminishing Lag Increment 5
Management of Aircraft Turn Capability 8
Altitude Increment 12
Rules for Choosing V_{BBD} 15
Load Factor Considerations 16
Thrust Considerations 19
TACTICS-II Computer Model 20

III. ENGAGEMENT RESULTS 22
Basic Fighter Maneuvers 22
Extended Dogfights 26
Trajectory Comparisons 27
Conversion Time Comparisons 34
Concluding Remarks 37

REFERENCES 39

I. INTRODUCTION

An important part of the development of U.S. Air Force fighter weapon systems is the evaluation of their performance in close-in dogfight environments. In 1969, Rand completed development of the TACTICS computer model, which can simulate a wide variety of aerial encounters--e.g., aircraft versus aircraft, air-to-air missiles, or surface-to-air missiles.[1] However, the original program did not contain the logic required to simulate extended dogfights; therefore, Rand undertook to develop the necessary maneuver logic. This report presents the rationale on which the new maneuver logic for fighter aircraft is based, discusses its incorporation into the original Rand simulation model to produce the TACTICS-II model, shows examples of dogfight engagements generated using this logic, and evaluates their realism.

During the past few years, many attempts have been made to develop the optimum logic or tactics required to computer-model close-in, air-to-air engagements. Optimum closed-form solutions to this problem have so far eluded analysts. One successful method of developing realistic "near-optimum" logic has been to define a decision-tree of tactics and maneuvers based on the experience of expert pilots, and then to monte carlo the tactics.

The approach presented in this report is quite different. Although not based on a closed-form solution to the problem of defining optimum maneuvers, it is essentially analytical and is derived from the fundamental physics of the combat situation. The guidance logic used by each aircraft is based on what may be a unique offset-diminishing-lag, pursuit-type guidance scheme. The salient feature of this logic is that the aircraft is directed to fly a pursuit course on some point behind (or to the side) and above or below the opponent aircraft; the magnitude of this lag is a function of the performance capabilities of each aircraft and their relative orientations to each other and the ground, and hence changes continuously throughout the simulated engagement.

This maneuver logic adheres to the basic objective of fighter pilots engaged in close-in, air-to-air combat--i.e., to gain a position from which to fire a weapon (missile or gun) at the opponent aircraft, while denying the opponent any firing opportunities. The aircraft that can perform faster, tighter turns without losing excessive energy relative to its opponent is most likely to accomplish this goal. Consequently, the logic developed to simulate dogfights directs each aircraft to maintain high turn rates and small turn radii as long as possible, insofar as they are compatible with good energy management. The technique for achieving this is to choose the proper mix of bank angle, lateral acceleration, and thrust, based on the particular aircraft's turn capability. The logic allows the aircraft to increase or decrease its speed, depending on the situation, by varying altitude, load factor, thrust level, or any appropriate combination of these, much as a pilot does in a dogfight environment.

Of course, turn capability management or energy management cannot be performed independent of the relative position and orientation of the opponent if the aircraft is to achieve a firing position. These commands must be coupled with those dictated by a pursuit command if the resultant maneuvers are to be effective against the opponent. Therefore, this turn-capability management logic, which directs the aircraft to fly above or below the opponent, is combined with a guidance scheme that directs the aircraft to fly a diminishing-lag pursuit course on the opponent. The result of this coupling is to define a point that is both behind (or to the side) *and* above or below the opponent, on which the aircraft flies pursuit.

Section II details this guidance logic for fighter aircraft and briefly describes its incorporation into the Rand TACTICS-II computer model. Section III then shows the results of dogfights generated by this logic and discusses their correlation with basic fighter aircraft maneuvers and available data on flight test combats.

II. DOGFIGHT MANEUVER LOGIC

The objective of the dogfight maneuver logic is to direct a fighter aircraft to attain, if possible, a weapon (missile or gun) firing position without allowing the opponent aircraft any firing opportunities. The preferred firing position is inside the opponent's rear hemisphere, because it affords the fighter the most firing time, while denying the opponent any firing opportunities.† However, the logic does not exclude shorter-duration opportunities to fire from inside the opponent's front hemisphere. It directs the aircraft to obtain these frontal firing opportunities, especially near the beginning of a dogfight, since they are usually easier to accomplish and are, in general, the first type of firing opportunity to occur in a dogfight situation.‡

As stated in Sec. I, the dogfight maneuver logic is basically a pursuit navigation scheme. However, it differs from pure pursuit guidance in that the fighter does *not necessarily always* fly pursuit on the opponent itself. Instead, the fighter is directed to fly pursuit on some point in the vicinity of the opponent aircraft. The location of this point, herein termed the *dogfight pursuit point*, relative to the target aircraft is a function of the relative positions and orientations of the two aircraft, their total and relative energy states, and their sustained and maximum turn capabilities.

Figure 1 illustrates the geometric relationship between two fighter aircraft when one is attempting to achieve a firing position against the other. Represented in the figure are both the *dogfight pursuit point* and the classic *pure pursuit point*, i.e., the target aircraft itself. If the attacking aircraft were to follow the pure-pursuit guidance law against its opponent, then the attacker would bank or roll into the

---

†This is true for current and projected near-term air-to-air ordnance.

‡As all-aspect weapons become available that can be used effectively in the close-in, air-to-air combat environment, the frontal firing opportunity will become more important. (All-aspect weapons are those that can be fired at an opponent aircraft regardless of the target's orientation relative to the weapon.)

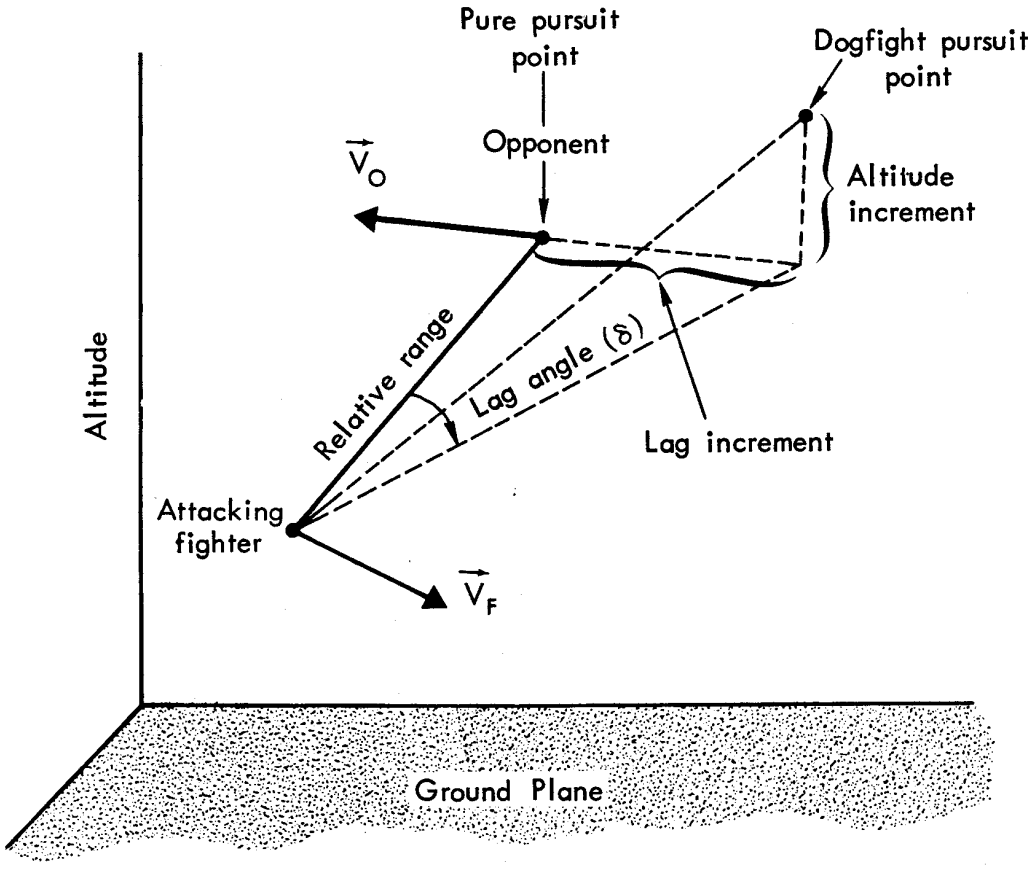

Fig.1 — Dogfight pursuit geometry

geometric plane defined by its velocity vector and the relative range vector, and execute the maximum load factor available. This is essentially the type of guidance used by most missiles and is also the last-ditch evasive action ("break") taken by an aircraft on the defensive when it is being fired on. However, as is well known to fighter pilots, this type of maneuver is not always appropriate during a dogfight and is only one of several described in the basic maneuver manual.[2]

As shown in Fig. 1, the dogfight pursuit point is defined by two components--a lag increment along the opponent's velocity vector (defined by some specified amount of lag angle) and a vertical or altitude increment. The lag increment is used to bias the attacking fighter to approach the opponent from the opponent's rear hemisphere, if possible. As demonstrated below, this lag increment and the corresponding lag

angle diminish in magnitude as the attacker begins to attain the dominant attack position, and thereby approaches a pure pursuit course. The altitude increment, which may be either positive or negative, is used to regulate the attacker's speed and total energy, relative to the opponent's speed and energy and its own turn capability. As discussed below, this increment also diminishes as the attacking fighter begins to be able to "track" (i.e., point its nose or its velocity vector at the opponent), and thus moves the dogfight pursuit point nearer the opponent's altitude.

DIMINISHING LAG INCREMENT

The function of the lag component of the dogfight pursuit point is to direct the fighter into a firing position within the opponent's rear hemisphere, without sacrificing possible firing opportunities in the front hemisphere. To do so, it is assumed that the desired amount of lag (lag angle δ) should be maximum when the attacking fighter is in the opponent's front hemisphere, and that the lag angle δ should decrease to a minimum of zero as the attacker moves into the opponent's rear hemisphere and its angle off the opponent's tail θ decreases. Furthermore, it is assumed that the magnitude of the lag angle δ depends only on the attacker's angle off the opponent's tail θ and that it should vary linearly from a maximum of δ_o for an angle-off of 180 deg to 0 deg for an angle-off of θ^* or less.[†] The value of θ^* is defined as the value of θ for which the attacking aircraft has sufficient load-factor capability, η_{max} (for the particular relative range and aircraft speeds), to instantaneously attain a pure pursuit course, if the attacker's velocity vector were pointed directly at the opponent. Figure 2 depicts the geometry for this situation. As shown, the angular rate of rotation of the line of sight relative to the attacker is given as $|\vec{V}_O| \sin \theta/R$, and the fighter's maximum angular turn rate is given as

$$\frac{\eta_{max}\, g_o}{|\vec{V}_F|}.$$

[†]As shown below, when the angle off the opponent's tail is about 180 deg (i.e., the attacking fighter is almost directly in front of the

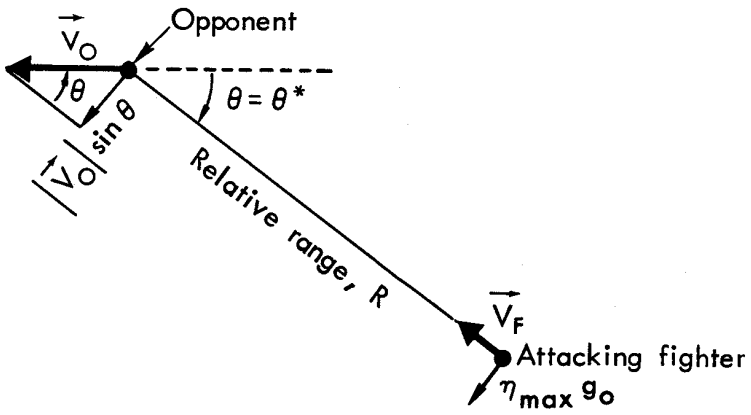

Fig.2 — θ^* geometry

Therefore, if θ^*, as defined above, corresponds to the value of θ for which these two angular rates are equal, then

$$\theta^* = \sin^{-1}\left(\frac{R\eta_{max}\, g_o}{|\vec{V}_F|\ |\vec{V}_O|}\right). \tag{1}$$

Furthermore, assuming the lag angle δ to be a linear function of the angle off the opponent's tail, then δ is given as follows:

$$\delta = \frac{\delta_o(\theta - \theta^*)}{180° - \theta^*} \qquad \text{for } \theta > \theta^*$$

or (2)

$$\delta = 0.0 \qquad \text{for } \theta \leq \theta^*.$$

---

opponent, such that $\delta > (180° - \theta)$), the lag increment lies to the side of the opponent instead of behind and along the opponent's velocity vector.

The value assigned to δ_o depends on the importance of firing opportunities in the front hemisphere. If the attacking fighter is equipped with reliable all-aspect dogfight missiles, then δ_o should have a small value, say 5 deg. However, if it is equipped with only rear-aspect weapons, then firing opportunities in the rear hemisphere are the only ones of interest and δ_o should have a somewhat larger value, say 15 to 20 deg.

Figure 3 illustrates how the magnitude of this lag increment x is calculated or, more important, how the relative lag-range vector $\overrightarrow{RLAG}$ is determined from the calculated lag angle δ and the relative orientation of the two combatants. The relative lag-range vector $\overrightarrow{RLAG}$ locates a lag pursuit point in space relative to the attacking fighter, just as the relative range vector $\vec{R}$ locates the pure pursuit point (opponent) relative to the attacker. Applying the law of sines to the geometry shown in Fig. 3 determines the magnitude of the lag increment as follows:

$$x = \frac{|\vec{R}| \sin \delta}{\sin (180^\circ - \theta - \delta)}, \tag{3}$$

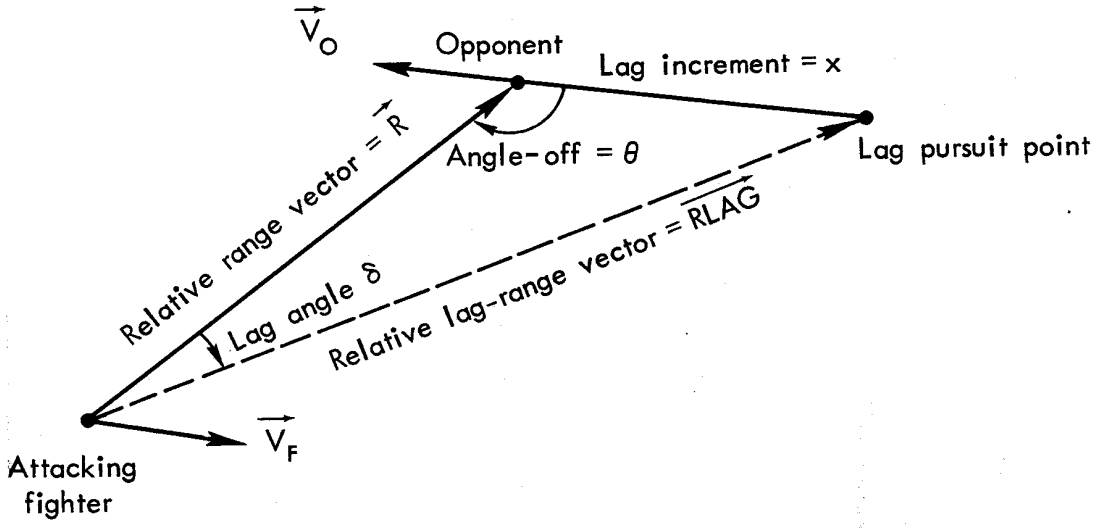

Fig.3 — Lag geometry

which in turn determines the relative lag-range vector as:

$$\overrightarrow{RLAG} = \vec{R} - \frac{x\vec{V_0}}{|\vec{V_0}|} \qquad \text{for } (180° - \theta) \geq \delta. \tag{4}$$

This equation for $\overrightarrow{RLAG}$, Eq. (4), places the lag pursuit component of the dogfight pursuit point directly behind the opponent aircraft, along the opponent's velocity vector. However, when the attacking fighter is almost directly in front of the opponent, such that $\delta > (180° - \theta)$, there is no value of lag increment behind the opponent (along the opponent's velocity vector) that corresponds to the desired lag angle δ.† In this situation, the lag point, as defined by $\overrightarrow{RLAG}$, lies behind and to the side of the opponent and is given as follows:

$$\overrightarrow{RLAG} = \frac{x\vec{V_0}}{|\vec{V_0}|} - \vec{R} \qquad \text{for } (180° - \theta) < \delta, \tag{5}$$

where the minimum value of $|\overrightarrow{RLAG}| = |\vec{R}|$. Its distance to the side and behind depends on the importance of firing opportunities in the front hemisphere, i.e., the assigned value of δ_o discussed above.

MANAGEMENT OF AIRCRAFT TURN CAPABILITY

As indicated in Sec. I, the objective of the dogfight maneuver logic is to direct the aircraft to fly in that portion of its flight region that results in high turn rates and small turn radii for prolonged periods. The premise is that the aircraft that is capable of performing faster, tighter turns, while not losing excessive energy relative to its opponent, should be able to achieve the most firing opportunities, while minimizing the opponent's firing opportunities. This capability is accomplished by choosing the proper mix of bank angle, lateral acceleration, and thrust such that the aircraft can fly for a

†In this situation, δ is nearly equal to δ_o.

prolonged period in the velocity region in which it has high turn rates and small turn radii. The desired bank angle is set essentially by the calculated altitude increment (Δh) of the dogfight pursuit point shown in Fig. 1; the lateral acceleration is determined by the aircraft's desired turn rate; the thrust setting is dependent on the aircraft's current and desired velocities.

The interrelationship of these variables can best be illustrated with the aid of a "turn capability diagram" such as the one presented in Fig. 4, which depicts all important turn performance parameters for an aircraft at a given altitude and weight.† The figure shows both the maximum possible instantaneous and steady-state turn rate and associated turn radius capabilities for a particular aircraft as a function of Mach number. It also displays the corresponding values of specific excess power (energy rate), P_s, throughout the aircraft's turn rate/Mach number flight region. As can be seen, the highest turn rates and smallest turn radii are associated with negative values of P_s; that is, the drag force is greater than thrust force. At lower speeds, the aircraft's maximum turn rate and minimum turn radius are limited by $C_{L_{max}}$ (i.e., q-limit); at higher speeds, they are limited by the aircraft's structural g-limit or the pilot's g-tolerance. The intersection of these two lines corresponds to the aircraft's maximum instantaneous turn rate (and, in general, minimum turn radius); the velocity at which this occurs is defined as the corner velocity. A previous analytical and numerical study of air-combat maneuvering concludes that optimum aircraft turn performance is obtained at or near this corner velocity.[3] Hence, it appears that a fighter aircraft engaged in air-to-air combat should attempt to fly in this region as much as possible.

However, the length of time an aircraft can maintain any given turn rate is a function of its specific excess power, P_s, and flight

†This method of plotting the data is a convenient way to display an aircraft's turn capabilities. Although the magnitudes of the turn rate contours do change with altitude, they change in a predictable manner (i.e., the turn rate increases as altitude decreases) and the general shape and characteristics of these diagrams for a particular aircraft do not change markedly throughout the primary dogfight altitudes.

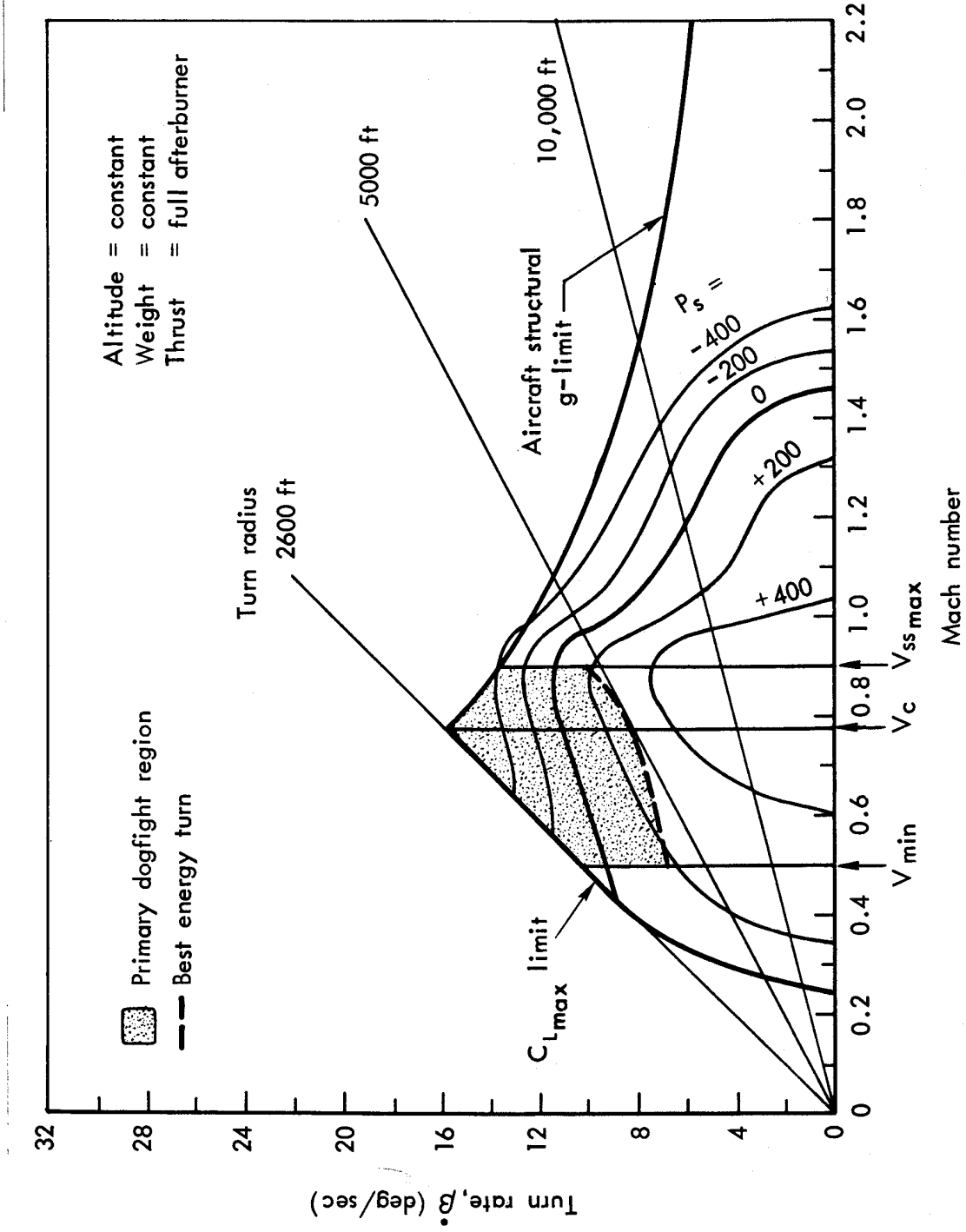

Fig. 4—Aircraft turn capability diagram

path angle. Anywhere on the $P_s = 0$ line, it can indefinitely maintain the same velocity at constant altitude with its corresponding turn rate. In Fig. 4, the maximum steady-state turn rate is about 11.5 deg/sec at a Mach number ≈ 0.9. If the aircraft is to increase its turn rate from the maximum steady-state rate to that of the corner velocity (16 deg/sec at $M = 0.77$), it must lose speed. However, as can be seen, this aircraft cannot long maintain the maximum turn rate associated with the corner velocity, because the corresponding value of P_s is large--less than -400 ft/sec. Thus, to maintain the corner velocity, the aircraft must either lose altitude or reduce its turn rate by reducing the load factor, or both.

Figure 4 shows that some regions of the turn rate/Mach number flight region are inapplicable to dogfight-type, close-in, air-to-air combat. For this particular aircraft, speeds above Mach 1 result in much lower turn rates and much larger turn radii than are possible with the steady-state conditions in the speed range below Mach 1. Also, higher speeds subject the pilot to higher g-levels for given turn rates. At moderately low flight speeds, say below $M = 0.5$ for this particular aircraft and altitude, it appears that the aircraft loses substantial turn rate capability, even though it can maintain the minimum turn radius condition. At very low speeds, however, the turn radius eventually begins to increase rapidly. Furthermore, at very low speeds, any fighter has very little kinetic energy to draw on in case emergency evasive actions are required (e.g., because another enemy aircraft is in the area). If its P_s characteristics resemble those of the aircraft presented in Fig. 4, it will not be able to readily increase its speed even at zero turn rate ($P_s < +300$ ft/sec).

It thus appears that the proper flight speed range for a fighter aircraft during a dogfight can be determined by examining its turn capability diagrams for the altitude and aircraft weight condition of interest. For the aircraft and altitude conditions presented in Fig. 4, which are representative of modern fighter aircraft at typical dogfight altitudes, it appears that the fighter should operate at high subsonic speeds.[†]

[†]Similar results as to the best speed range for modern fighter aircraft involved in close-in aerial engagements were obtained by Lt. Col. John Boyd from his work in expanded energy maneuverability.[4]

Altitude Increment

The discussion of the aircraft turn capability diagram shows that, during the course of an engagement, the dynamics of the dogfight result in an aircraft exchanging velocity for turn rate and vice versa, as determined by its specific excess power. Any desired velocity may be attained partially by adjusting the aircraft's bank angle, i.e., to dive or climb. The mechanism for mathematically determining the appropriate bank angle is to calculate the desired altitude increment (Δh) that forms the other component of the $\overrightarrow{RLAG}$ vector and thereby defines the dogfight pursuit point displayed in Fig. 1.

As discussed above, the maximum and minimum velocity limits can be determined by calculating the velocity corresponding to the maximum steady-state turn rate, $V_{ss_{max}}$; the corner velocity, V_c; and a minimum desired velocity, V_{min}. As shown below, V_c and $V_{ss_{max}}$ are used as potential velocities† to drive the altitude increment Δh, which in turn regulates the aircraft's bank angle. V_{min} is used to indicate that the aircraft's commanded load factor should be reduced from some higher nominal value if the aircraft's speed becomes less than V_{min}, as discussed on p. 18; that is, the fighter will need to decrease its lateral acceleration (so that aircraft drag will be less than thrust) in order to increase speed or altitude or both.

During most of a dogfight (except the firing opportunities), each aircraft should attempt to drive the combat to the nearest altitude that permits it to achieve its best turn velocity (V_{BBD}), which is usually $V_{ss_{max}}$ or V_c, depending on the situation. However, under these conditions, the aircraft's speed should stay within the limits prescribed by turn capability diagrams in order to maintain high turn rates and small turn radii as much as possible. Thus the need arises for the altitude increment Δh such that the aircraft will fly pursuit on the opponent *and* at the same time strive for the desired change in altitude and corresponding change in velocity.

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†For some aircraft and altitude combinations, V_c is greater than $V_{ss_{max}}$; in these cases, V_c may be the potential driving velocity for some parts of the combat.

The shift in altitude required to change the aircraft's velocity from V to the best turn rate velocity V_{BBD} is a function of several terms, the first of which is

$$\frac{V^2 - V_{BBD}^2}{2g_o}.$$

This term represents the exchange between total kinetic energy and potential energy that must take place before the aircraft's speed reaches V_{BBD}.† However, simply attaining the altitude and the desired speed V_{BBD} is not sufficient; the amount of kinetic energy that is vertical kinetic energy must also be taken into account. For example, if the aircraft reaches the desired altitude and attains a speed of V_{BBD}, but has a flight path angle very different from zero (i.e., a steep dive or climb), then it will be unable to stay in the preferred speed range. That is, the aircraft will gain or lose more altitude and speed than desired before it can pull out of the dive or climb. Moreover, in doing so, it will expend considerable turn energy. Therefore, a second term is necessary to compute Δh properly, one that accounts for the change in altitude required to reduce the vertical component of total kinetic energy to zero. If the change in vertical kinetic energy is accomplished by a mere net 1-g acceleration in the vertical (i.e., the aircraft lift vector is primarily in the horizontal plane),‡ then the corresponding change in altitude that must occur before the vertical kinetic energy will be reduced to zero is given by

$$\frac{+V^2 \sin\gamma \, |\sin\gamma|}{2g_o},$$

†Of course, this term assumes that during the trade between altitude and velocity, the net drag and thrust contribution to kinetic energy is small. This will nearly be the case as long as the aircraft maintains turn rates that are close to the $P_s = 0$ contour.

‡For a large part of the combat, this will be the case since the two aircraft will be in the same altitude range and primarily pulling g's into each other.

where the flight path angle γ is defined as positive up and negative down.

One other important parameter must be accounted for if a fighter is to attain the altitude corresponding to the desired value of V_{BBD}, while flying pursuit on an opponent: the current altitude differential between a fighter and its opponent $(h_F - h_O)$. Therefore, the complete equation for calculating the altitude increment of the dogfight pursuit point when a fighter needs to attain a speed of V_{BBD} to perform faster or tighter turns or both is given by

$$\Delta h = \frac{\left[V_F^2 - V_{BBD}^2\right]}{2g_o} - \frac{V_F^2 \sin\gamma \,|\sin\gamma|}{2g_o} + (h_F - h_O). \qquad (6)$$

Now, as stated previously, when the attacking fighter is nearly able to track the dogfight pursuit point (i.e., the usually very large commanded lateral acceleration approaches the maximum aircraft lateral g-capability), the Δh increment must be decreased so that the dogfight pursuit point will move closer to the opponent. As a result, if the attacker is able, it will finally track on the pure pursuit point (the opponent) and attain firing opportunities. To accomplish this transition, the Δh increment is appropriately reduced by modifying Eq. (6) by a multiplier, K, as follows:

$$\Delta h = K \left\{ \frac{\left[V_F^2 - V_{BBD}^2\right]}{2g_o} - \frac{V_F^2 \sin\gamma \,|\sin\gamma|}{2g_o} + (h_F - h_O) \right\}, \qquad (7)$$

where

$$K = \left[\frac{A_c - 10}{90}\right] \qquad \begin{array}{l}\text{max value } 1 \\ \text{min value } 0\end{array}$$

and A_c is the lateral acceleration (g's) commanded by the pursuit guidance law. As A_c approaches a value of 10 g, which is above the maximum

load factor capability of most fighter aircraft, then the value of K goes to zero, and hence the altitude increment goes to zero.

Rules for Choosing V_{BBD}

As indicated above, the best turn rate velocity V_{BBD} is generally either V_c or $V_{ss_{max}}$. The choice depends on the characteristics of the turn capability diagram for the specified set of conditions.

For example, during the initial phase of an aerial encounter, when a fighter may be either making an IFF (Identification, Friend or Foe) run on a potential threat or attempting to attain a higher velocity and thus gain energy that can be used against a subsequent threat, the value of V_{BBD} to be used in calculating the desired Δh should be either V_c or $V_{ss_{max}}$, whichever is greater. If $V_{ss_{max}}$ is greater than V_c, as in the case presented in Fig. 4, and the fighter has sufficient time and thrust to achieve a speed of $V_{ss_{max}}$, then the fighter has all of the turn capability available in the negative P_s region from $V_{ss_{max}}$ down through V_c and below, if necessary. If the fighter does not choose to attain this higher velocity, then this velocity/turn rate range will not be initially available unless the fighter gives up altitude. Similarly, if V_c is greater than $V_{ss_{max}}$, then the fighter should attempt to reach a speed of V_c before the initial pass is completed, so that it will have the highest possible turn rates and the smallest possible turn radii available from the beginning of the engagement.

After the initial encounter phase, the value of V_{BBD} should remain either V_c or $V_{ss_{max}}$ (again depending on the relative orientation and energy state of the turning aircraft) and is used as the driving potential speed to keep the fighter's speed and energy near the maximum end of the aircraft's dogfight speed range. If the fighter can attain V_{BBD}, then it can use this speed and energy to achieve the highest turn rates available to either complete the conversion or ward off the opponent's attempt to convert to a weapon firing position.

However, the value of V_{BBD} used in Eq. (7) should not always correspond to the velocity associated with the aircraft's best turn speeds. For example, when an attacking fighter approaches a firing position in the opponent's rear hemisphere, the opponent aircraft's speed and load

factor level must be taken into account, if the attacker is to maintain the dominant positional advantage once it has been attained. To do so, the fighter must eventually match the opponent's speed; under these conditions, the opponent's speed is the potential velocity that drives the altitude increment.

Load Factor Considerations

As shown above, turn capability diagrams like that presented in Fig. 4 can be used to define the desired velocity range applicable to dogfights. The characteristics of this diagram are used to determine the value of Δh, which in turn dictates the bank angle, one of the aircraft's three primary control parameters. Similarly, the turn capability information presented in the figure, together with the corresponding aircraft load factor diagram in Fig. 5, can be used to define the load factor range in which a fighter aircraft should operate. The load factor diagram shows the maximum possible lateral acceleration that the aircraft can execute as a function of its speed for a given altitude and weight. The diagram also displays the P_s contours that show the maximum steady-state load factor that the aircraft can maintain and the energy gain or loss rates associated with the larger or smaller load factor levels. These P_s contours and load factor limits are the same as those shown in Fig. 4. The shaded area in Fig. 5 defines the region of the load factor diagram that corresponds to the high-turn-rate, small-turn-radius region shown in Fig. 4. As these two figures show, the aircraft can obtain the high turn rates and small turn radii (Fig. 4) only by executing the corresponding, generally large, lateral accelerations (Fig. 5).

As may also be seen in these two figures, if the aircraft operates in the $\dot{\beta}$ and n region above the $P_s = 0$ contours, as it must do during certain parts of a dogfight, then the aircraft must lose speed or altitude or both, and trade potential energy for kinetic energy and speed. It appears that a fighter having turn capabilities similar to those shown in Figs. 4 and 5 cannot afford to operate at the maximum turn rate and load factor indefinitely, because the magnitude of the P_s contour near the maximum $\dot{\beta}$ indicates that the aircraft would quickly

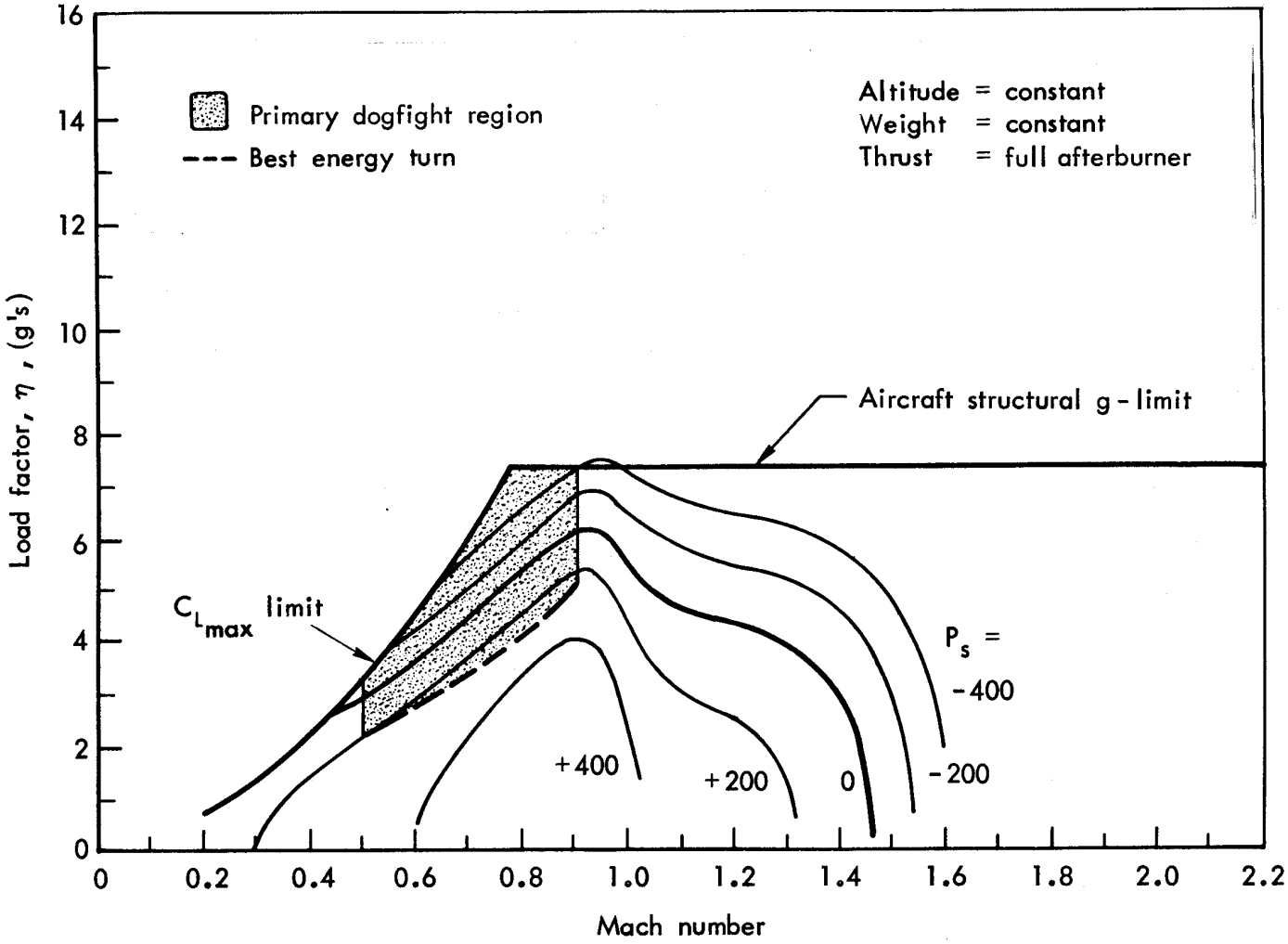

Fig.5 — Aircraft load factor diagram

decelerate. Therefore, to stay in the high-turn-rate, small-turn-radius region (the shaded areas shown in Figs. 4 and 5), the aircraft must fly some load factor time-history, the average of which is less than the maximum possible.

In general, if an aircraft's speed is about $V_{ss_{max}}$ during the initial and conversion phases of a dogfight (during which neither aircraft is near a firing position), then it should execute the value of load factor that corresponds to the maximum steady-state turn rate, $n_{ss_{max}}$. If an aircraft's velocity is much different from $V_{ss_{max}}$, or if it has gained a significant positional or energy advantage over its opponent, then the aircraft should use some value of load factor other than $n_{ss_{max}}$, depending on the relative positions, velocities, and energy states of the two aircraft. For example, if an attacking fighter is approaching a firing position in its opponent's rear hemisphere and also has an energy advantage over the opponent, then the attacker should execute maximum load factor to attain a high turn rate and ensure the firing opportunity.

If during the course of the combat an aircraft has reduced its speed to V_{min}, by attempting to either ward off its opponent or match its velocity to obtain firing opportunities, it may have to increase its speed to regain higher turn rates. However, if it cannot lose any more altitude, then it must decrease its turn rate (by decreasing its load factor) to below the $P_s = 0$ contour. Just how far below the $P_s = 0$ contour an aircraft should operate during this "speed-up" phase of the combat has been the subject of much discussion, and no one, to the authors' knowledge, has derived a mathematical proof for the optimum load factor history. However, it seems apparent that even during such a phase of the combat, an aircraft must attempt to prevent its opponent from gaining too much positional advantage. Therefore, although an aircraft would probably gain the largest possible longitudinal acceleration by so reducing its load factor that it would fly in a nearly straight line, the aircraft should not use this tactic because it would permit the opponent to gain the dominant positional advantage easily and quickly. Instead, it should maintain some moderate turn rate that will allow it to gain speed efficiently--e.g., obtain some lift for a small drag penalty.

Boyd and Christie treat this point in their work on expanded energy maneuverability. In their search for an efficient turn, they developed what they call a "best energy turn" that directs the aircraft to fly along a load factor/velocity history that corresponds to the aircraft's maximum lift-to-drag ratio or the maximum of the product of P_s and $\dot{\beta}$. In any event, it is the contention here that, under the conditions for which both longitudinal acceleration and turning are necessary, some such efficient turn should be used, which would result in a moderate value of turn rate and a positive P_s. The line drawn as the lower limit of the primary dogfight region in Figs. 4 and 5 represents a combination of $(L/D)_{max}$ and $(P_s\dot{\beta})_{max}$, whichever yields the greater turn rate at each Mach number.

Thrust Considerations

The P_s contours displayed in the turn capability diagram, which is representative of existing modern fighter aircraft, show that throughout most of a dogfight a fighter is limited by insufficient thrust. If a fighter had sufficient thrust, it would fly at the corner velocity for most of the combat, to obtain the aircraft's optimum turn performance, as discussed in Ref. 3. However, since all current and most projected fighters are incapable of sustaining the corner speed over the entire range of the dogfight altitude (up to 30,000 ft), it seems apparent that for most of the maneuvering part of a dogfight engagement a fighter will use its full afterburner (maximum thrust) capability. However, even for these generally thrust-limited fighters, there are at least two situations in which it may be necessary to reduce the aircraft's thrust level below maximum thrust--i.e., during the initial and terminal phases of an encounter.

As discussed above, a fighter should attempt to attain a speed not much greater than the maximum of V_c or $V_{ss_{max}}$, particularly if it is in the higher region of the dogfight altitude spectrum or at an altitude above its opponent. In these instances, the fighter has two options for maintaining its speed--i.e., either reduce its thrust or climb, thereby gaining additional total energy. However, turn rate capability (both maximum and steady-state) decreases significantly with increasing altitude. Therefore, if the fighter gains too much altitude over its opponent, the opponent will have a turn rate/turn radius advantage and

might be able to get the first firing opportunity, or at least put the fighter on the defensive from the very beginning of the engagement.

The other situation in which it may be necessary to reduce thrust arises when the attacking fighter approaches a firing position from within the opponent's rear hemisphere. If the opponent "bleeds off" energy and speed in an attempt to force the attacker out of his rear hemisphere (to force overshoot), then the attacker may be required to reduce its thrust (and at the same time execute maximum load factor) in order to reduce speed and attain and maintain the dominant positional advantage.

TACTICS-II COMPUTER MODEL

This dogfight maneuver logic was implemented in a computer simulation model for air-to-air combat by expanding and modifying the TACTICS digital computer program developed at Rand in 1969. The original TACTICS model is a three-dimensional, 5-degrees-of-freedom (i.e., coordinated maneuvers) program designed to simulate the maneuvers of up to three vehicles simultaneously. It was developed primarily as a research tool for investigating in detail the mechanics, geometry, and vehicle-performance characteristics of aircraft and missiles for air-to-air combat. The program therefore emphasizes simulation flexibility and user control, with sufficient time-history printout of variables to allow a fine-grained analysis of air-to-air combat, as well as a broad variety of vehicle simulations. The flexibility to simulate many types of engagements is provided through a POLICY subroutine that may be written and modified by the user. This subroutine calls various "action" or "maneuver" subroutines for each vehicle, based on any user-specified criteria desired--e.g., time, angle, range, velocity. The TACTICS library of action subroutines includes open-loop maneuvers, such as turns and dives; and closed-loop maneuvers, such as pursuit and lead collision. The primary function of the maneuver subroutines is to calculate the lateral (normal to the velocity vector) acceleration required to maneuver the vehicle as desired--i.e., pull a 3-g turn or, in the case of pursuit, turn the vehicle (in a plane defined by the two aircrafts' relative range vector and the pursuer's velocity vector) to point at the opponent aircraft.

All of the dogfight maneuver logic described above was incorporated into a set of nine new subroutines. The variables of interest, such as the corner velocity and velocity for maximum steady-state turn rate, are determined for each computing interval. By testing and comparing these and many other computed variables, the program obtains enough information concerning each aircraft's actual and potential turn capabilities and desired velocity to be able to select the preferred equation for calculating the Δh increment. This increment is vectorially added to the basic lag increment (calculated in the diminishing-lag-pursuit maneuver subroutine) and the resultant vector locates the dogfight pursuit point. Using this as the point to fly toward, the maneuver subroutine then calculates the required lateral acceleration in the same manner as for the pure pursuit point. That is, a lateral acceleration is applied to the velocity vector, causing the pursuing aircraft to turn in a plane defined by its velocity vector and the vector from it to the dogfight pursuit point. For each computing interval, this dogfight pursuit point is recalculated; as the pursuing aircraft attains a tracking position, the point moves toward the opponent.

Incorporation of this logic into the TACTICS program also required defining additional data inputs, as well as printed output, to more fully describe the dogfight situation. Consequently, it was necessary to modify or expand a number of existing TACTICS subroutines. To distinguish the two programs, the dogfight version was named TACTICS-II; for fighter-versus-fighter combat with or without missiles, it can simulate the same variety of engagements as the original TACTICS, as well as the specialized extended dogfight situation.

III. ENGAGEMENT RESULTS

After the dogfight guidance scheme discussed in Sec. II was incorporated into the Rand TACTICS model, a variety of engagements was generated to determine whether the logic simulates realistic fighter aircraft maneuvers and dogfights. These TACTICS-II trajectories were compared with those from two sources of maneuvers and engagements--the basic fighter maneuvers used by USAF fighter pilots[2] and the mock dogfights flown during the Project Combat Hassle flight test program.[5]

BASIC FIGHTER MANEUVERS

The air-to-air combat tactics section of Ref. 2 describes a variety of basic maneuvers--such as the defensive turn, scissors, high-speed yo-yo, low-speed yo-yo, and diving spiral--that experienced USAF pilots have found effective in various air combat situations. Each maneuver is applicable to a particular situation and is designed to help the pilot to either gain the advantage or counter an enemy's advantage. These basic fighter maneuvers are learned by U.S. fighter pilots and are used as the basis for their overall air combat tactics.

To determine whether the TACTICS-II dogfight logic would automatically and realistically simulate these basic fighter maneuvers, the model was used to generate a set of short engagements, starting with the proper circumstances for each basic maneuver. The initial conditions were chosen such that the appropriate action should result in one of the basic fighter maneuvers by one of the two combatants.

For example, the high-speed yo-yo is used when an attacker finds himself closing on an enemy aircraft from behind, but is unable to obtain a firing position because the enemy is executing a defensive turn into the initial plane of attack and the attacker is flying too fast to turn with the defender. The high-speed yo-yo calls for the attacker to roll up slightly out of the initial plane of attack so as to gain altitude and lose air speed. With this lower speed, the attacker should be able to execute tighter turns, by pulling a high load factor, and thus not overshoot his position behind the enemy aircraft. Then

the attacker can roll slightly below the initial plane of attack and lose altitude, trading potential energy for turn energy to maintain the high turn rate and small turn radius. If the high-speed yo-yo is performed properly and the required turn performance is within the attacker's capability, the aircraft should convert to the dominant position off the enemy's tail.

Figure 6 presents the results of a TACTICS-II simulation for a set of initial conditions appropriate to produce a high-speed yo-yo. This figure shows the computer-generated graphical display of the top and front views of the trajectories of each aircraft for the simulated engagement.† As shown, the attacker (solid line) was located in the opponent's rear hemisphere with a Mach number of 0.95 and a lag heading angle of 45 deg. The defender (dashed line), initially at a Mach number of 0.82, was directed to execute and maintain a 5-g defensive turn into the initial plane of attack.‡ The attacker was directed to fly the incorporated dogfight logic. As the graph shows, the attacker performed a maneuver that looks very much like a high-speed yo-yo. The dogfight logic automatically directed the attacker to increase its altitude about 1000 ft while still maintaining a substantial turn into the defender. As a result, the attacker is able to track the opponent aircraft within the first 10 sec of the engagement, then close to a relative range of about 1900 ft (at an angle off the opponent's tail of 21 deg) within another 20 sec. This would not have been possible in such a short time had the attacker not executed the high-speed yo-yo maneuver.

Figure 7 presents the results of a TACTICS-II simulation for a set of initial conditions appropriate for another basic fighter maneuver, the low-speed yo-yo. In the circumstances for a low-speed

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† In addition to its standard numerical output, the TACTICS-II model produces time-position data in a form such that a computer-driven microfilm plotter can generate three-view plots of the trajectories of each vehicle involved, i.e., top, front, and side views of the engagement.

‡ In actual combat, the defender would not continue such a maneuver after it was evident that the attacker was not going to overshoot. However, the purpose of this engagement was to test the dogfight logic and to determine whether the attacker would automatically perform the appropriate maneuver if the defender maintained the initial defensive turn.

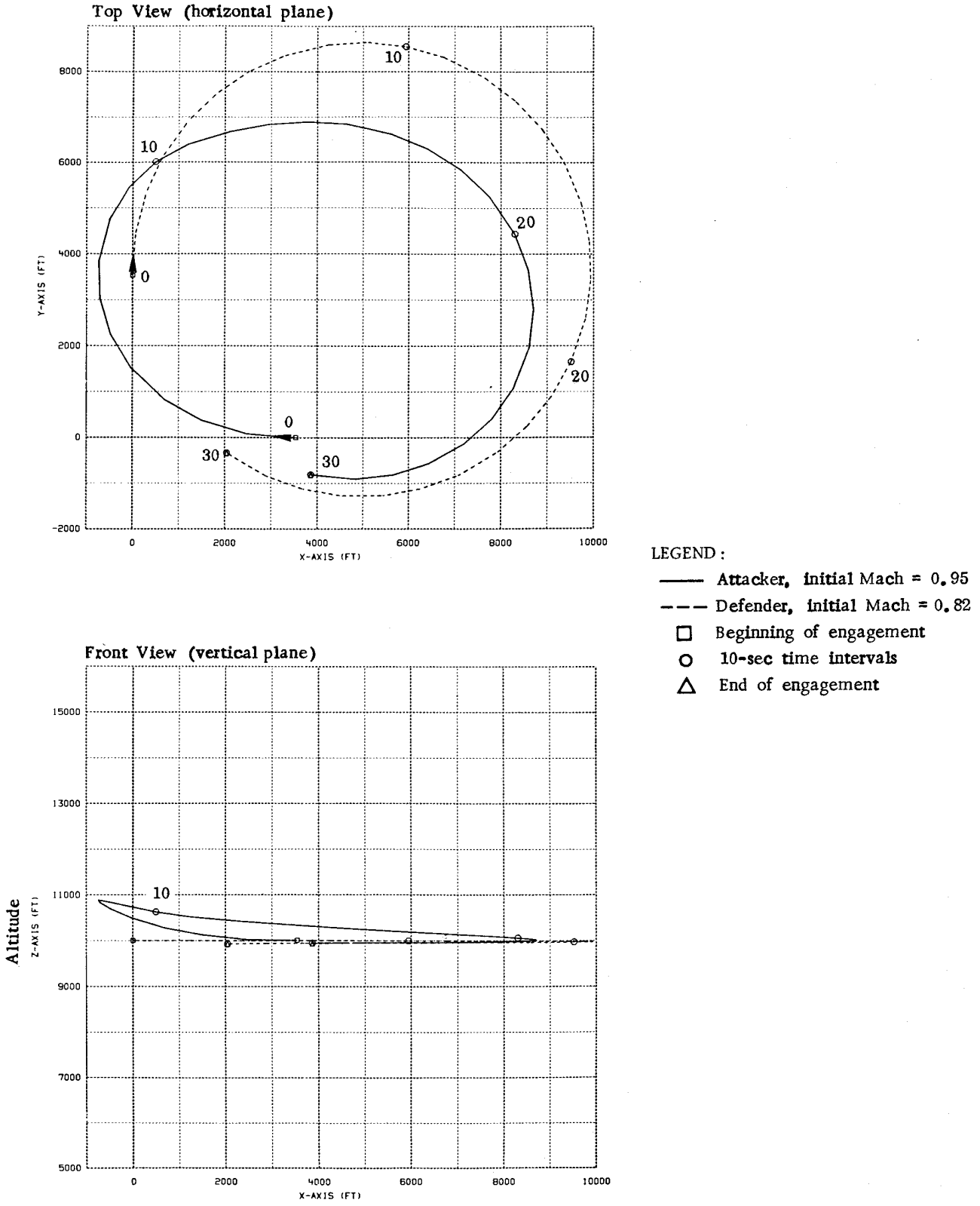


Fig.6 — Tactics-II simulation: high-speed yo-yo

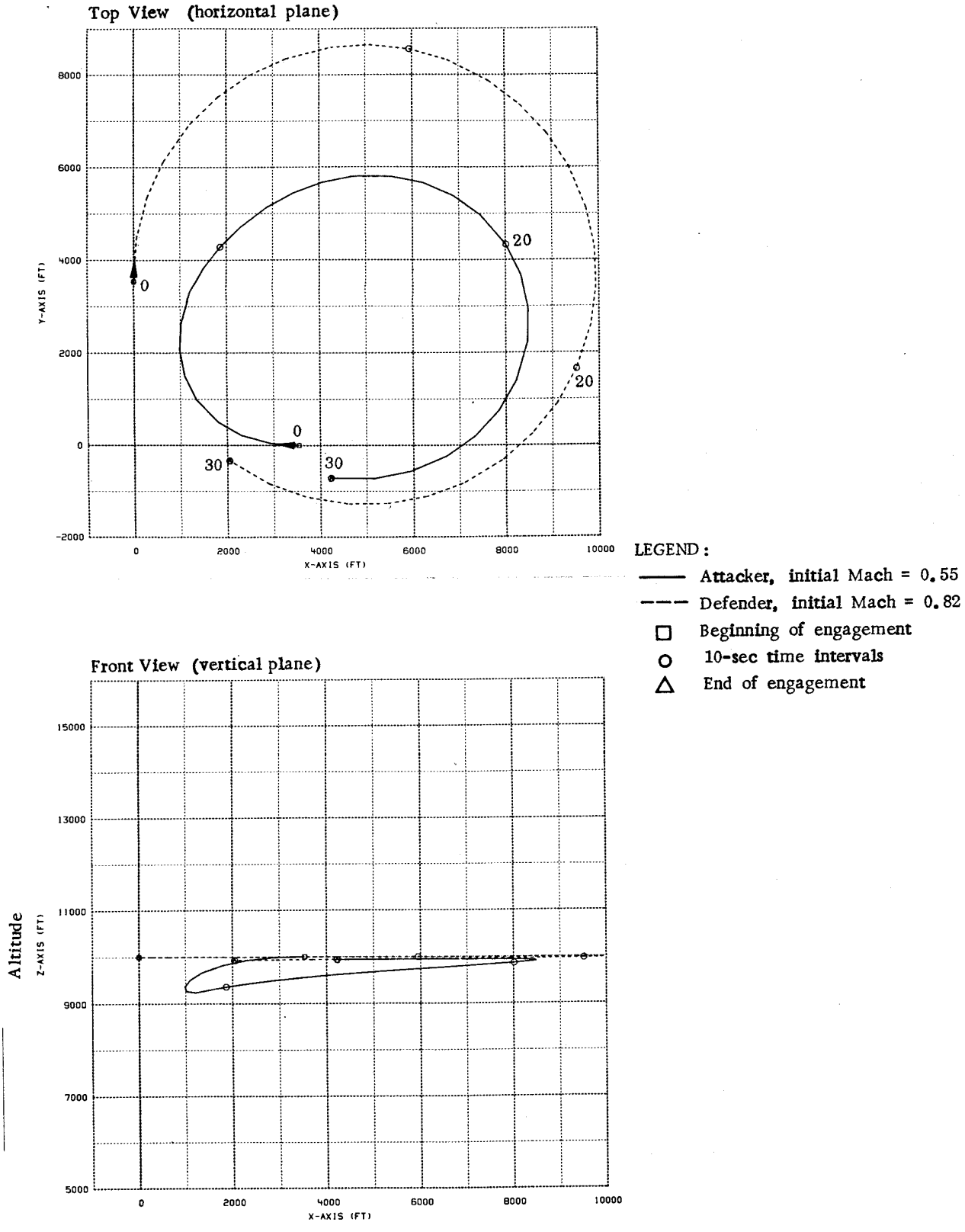


Fig.7 — Tactics-II simulation: low-speed yo-yo

yo-yo, the attacker finds himself in the same position relative to the defender as for the high-speed yo-yo except, in this case, the attacker's speed is much less than his opponent's. Although the attacker has a positional advantage, he is unable to capitalize on it and obtain a firing opportunity because the relative range is opening rapidly and his maximum possible turn rate is too low. Therefore, to be able to close on the defender and attain the dominant positional advantage, the attacker must dive slightly to increase air speed and turn rate. For the TACTICS-II simulation shown, the attacker's initial Mach number was set at 0.55 and the defender's at 0.82. As before, the defender was constrained to execute a 5-g turn in the initial attack plane and the attacker was directed to follow the dogfight logic. The simulation results in Fig. 7 show that the attacker automatically performed a maneuver resembling a low-speed yo-yo. The attacker dove and used about 800 ft of altitude to increase his air speed and turn rate. The attacker was able to commence tracking the opponent after 9 sec of engagement time, then closed to a relative range of about 2200 ft (angle-off 27 deg) at 30 sec.

This same procedure was performed for the other basic fighter maneuvers mentioned above, and similar comparative results were obtained. The dogfight logic in the TACTICS-II computer model appears to realistically simulate the basic fighter maneuvers, given the appropriate circumstances.

EXTENDED DOGFIGHTS

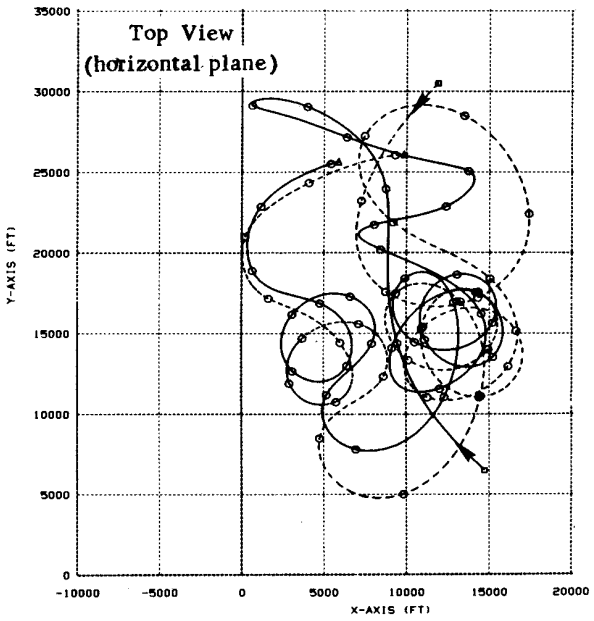
To determine how realistically the TACTICS-II dogfight logic can simulate close-in aerial combat, the program was used to produce extended dogfights and the results were compared with those generated by the Project Combat Hassle flight test program.[5] This Air Force program, conducted by the Armament Development and Test Center (ADTC) at Eglin Air Force Base in 1967, was designed to simulate a one-on-one, close-in, air-to-air combat environment. In this series of flight tests, two F-4D aircraft engaged in aggressive, close-in, mock air combat, with each aircraft attempting to attain a gun firing position on the other. Hence, the trajectories generated represented those of real aircraft

flown by real pilots and therefore reflected man-machine responses, limitations, and judgments.

During each Combat Hassle engagement, aircraft time-position data were recorded by ground radar; during each simulated burst of fire, an on-board "gun-sight" camera filmed the target aircraft. The objectives of this flight test program were (1) to measure the effectiveness of a thrust-to-weight (T/W) advantage in one-on-one, close-in, air-to-air combat, and (2) to provide flight test data in a form useful to analysts. To simulate T/W differences, various predetermined maximum throttle settings were imposed on one of the aircraft. That is, one aircraft was limited to a maximum thrust level corresponding to either full military power, one-third afterburner, two-thirds afterburner, or full afterburner; the other was always allowed full afterburner thrust capability. To fully investigate these four different maximum throttle settings for a combination of two aircraft and three pilots, 82 five-minute engagements were flown. For each engagement, ADTC performed data reduction of the ground-based radar data to obtain smooth position histories of each aircraft.

Trajectory Comparisons

Figure 8 presents three-view plots of a typical Combat Hassle engagement between two F-4Ds, one limited to two-thirds afterburner and the other permitted full afterburner capability. These three views of the trajectories of the two aircraft for this three-dimensional dogfight were generated by Rand, using ADTC's position-history data and a computer-driven microfilm plotter. The flight test program specified that each engagement was to begin with both aircraft at an altitude of 25,000 ft, a separation range of 24,000 ft, a speed of Mach 0.85, and a flight-path crossing angle of 90 deg. However, as Fig. 8 shows, the actual initial conditions were not always identical to the specified initial conditions. In general, at the start of each Combat Hassle engagement, the aircrafts' altitude, speed, and flight-path crossing angles were close to the nominal values, but their initial relative range often varied significantly from 24,000 ft. Furthermore, a review of all Combat Hassle engagements showed that, in general, neither

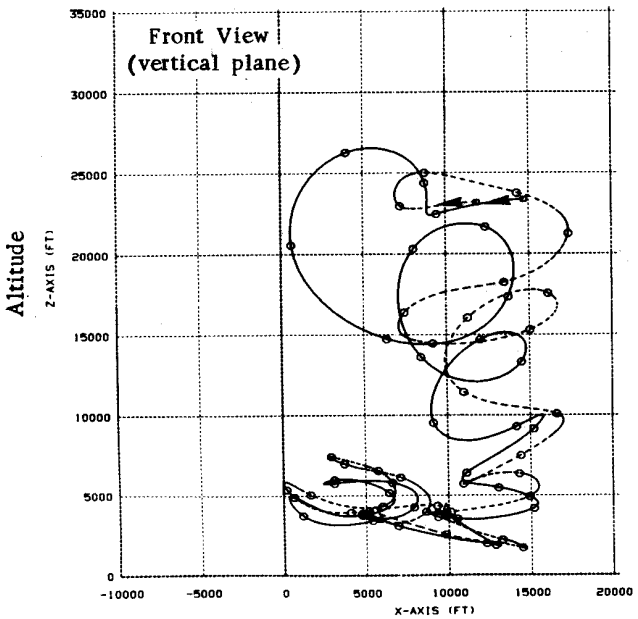


NOMINAL INITIAL CONDITIONS:

Altitude = 25,000 ft
Mach = 0.85
Range = 24,000 ft

LEGEND:

——— Aircraft with full afterburner capability
– – – – Aircraft limited to 2/3 afterburner
□ Beginning of engagement
○ 10-sec time intervals
△ End of engagement



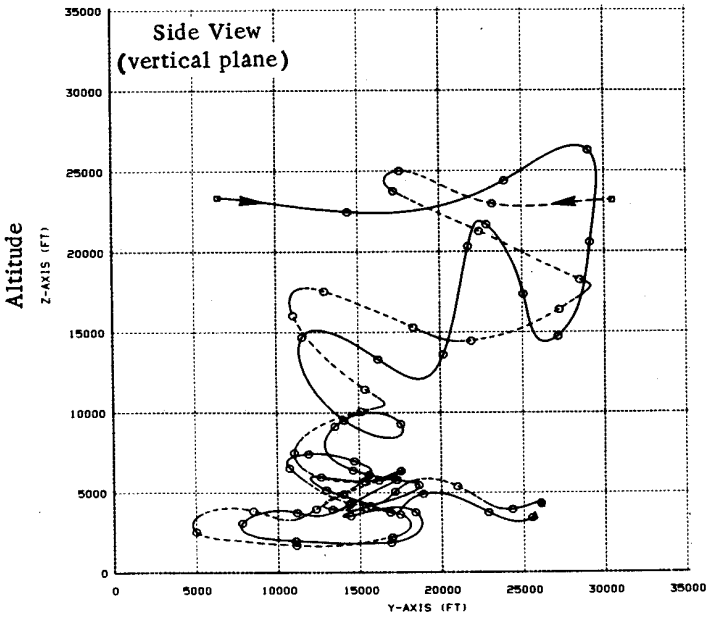


Fig. 8 — Typical Combat Hassle engagement: full afterburner versus 2/3 afterburner

aircraft started to maneuver before the relative range decreased to about 3 nm.[†]

The solid line in Figs. 8 through 11 represents the trajectory of the aircraft with full afterburner capability, and the dashed line defines the trajectory of the one with limited thrust. In Fig. 8, the dashed-line trajectory signifies two-thirds afterburner. As Fig. 8 shows, particularly the top and side views, the aircraft with full afterburner thrust capability eventually attains and maintains the dominant positional advantage off the tail of the aircraft having the lower maximum thrust.

Figure 9 presents the results of a TACTICS-II simulated engagement between two F-4D aircraft, one limited to a maximum of two-thirds afterburner thrust and the other, full afterburner if desired. The initial conditions for this engagement are identical to the nominal initial conditions for Combat Hassle, except the aircraft were not allowed to commence maneuvering until the relative range decreased to 18,000 ft (about 3 nm), as in fact occurred in the actual Combat Hassle engagements.

Comparison of the two engagements in Figs. 8 and 9 reveals that, although they are not identical, they do appear to have many similar characteristics, especially in the use of the vertical plane. In both engagements, the aircraft yo-yo up and down in the vertical (perhaps more so in the Combat Hassle engagement, at least during its initial part), with the general trend being down; that is, in both engagements, both aircraft trade their initial altitude (potential energy) for turn energy in an attempt to gain a superior position.[‡] These engagement

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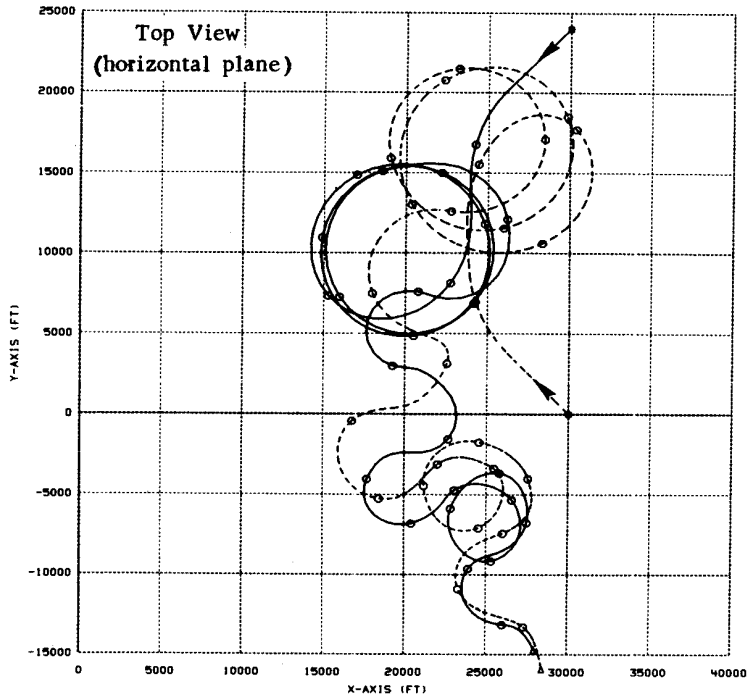
[†] This may have been due to visual limitations; that is, the relative range had to decrease to about 3 nm before each pilot could determine his opponent's attitude and maneuver plane.

[‡] An additional method of comparing these trajectories was employed for several Combat Hassle and TACTICS-II dogfights. Using Rand's computer-driven stereoscopic display system[6] and the time-position points defining the trajectories as input data, it was possible to obtain a real-time, three-dimensional display of each engagement as it evolved. This visual comparison of the dynamics of the combats revealed that the interaction and relative maneuvering by the two aircraft, for both the Combat Hassle and the TACTICS-II engagements, were so much alike in character that it was usually very difficult to distinguish the real engagements from the simulated.



INITIAL CONDITIONS:

Altitude = 25,000 ft
Mach = 0.85
Range = 24,000 ft

LEGEND:

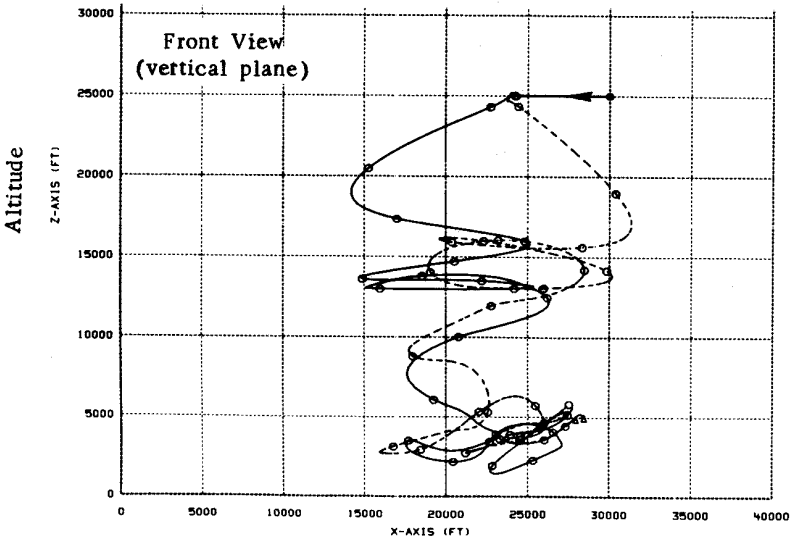
——— Aircraft with full afterburner capability

- - - - Aircraft limited to 2/3 afterburner

□ Beginning of engagement

○ 10-sec time intervals

△ End of engagement



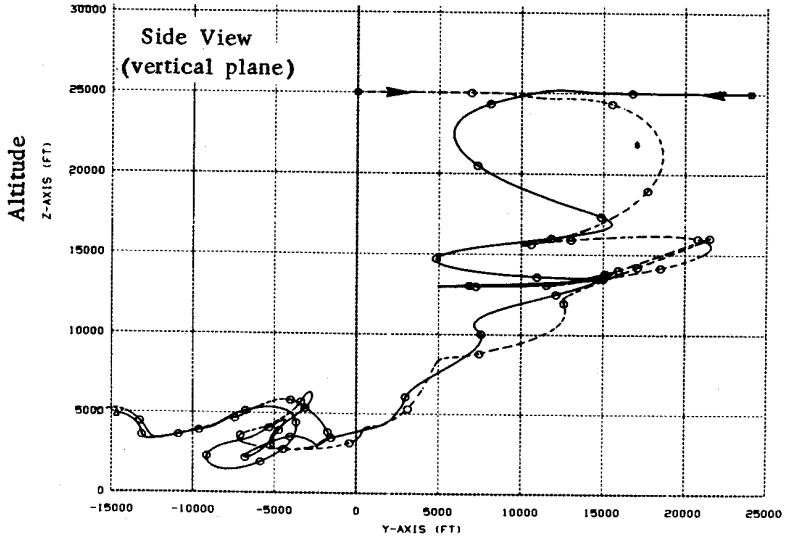


Fig.9 — Tactics-II simulation: full afterburner versus 2/3 afterburner

results demonstrate that the aircraft with the thrust-to-weight ratio advantage gains and maintains the dominant position. According to ADTC's analysis of the gun-sight camera film, the superior aircraft obtained its first gun firing opportunity (at a relative range of less than 3000 ft) after 272 sec of combat. An analysis of the numerical output for the corresponding TACTICS-II engagement shows that the aircraft with full afterburner capability obtained its first gun firing opportunity (range $\leq$ 3000 ft) after 217 sec. These two times-to-convert appear to be quite different; however, the initial conditions for the two engagements were not identical and, as discussed below, individual differences in pilots flying the same aircraft can contribute to the large spread in the Combat Hassle conversion times.

Figures 10 and 11 show another trajectory comparison between a typical Combat Hassle engagement and a corresponding TACTICS-II simulation. In these cases, the inferior aircraft was limited to one-third afterburner capability. Again, the two engagements are not identical, but they do have many similarities, such as tight turns, use of the vertical plane for yo-yos and counter yo-yos, and the overall use of the vertical plane. In this particular Combat Hassle engagement, the superior aircraft gained the dominant position and obtained a firing opportunity after 185 sec, although it had difficulty maintaining it, as evidenced by the end condition shown in the top view of Fig. 10. As for the corresponding TACTICS-II engagement, the superior aircraft achieved and maintained the dominant position after 166 sec of combat. In this case, the time-to-convert for both the flight test and the model are close, although the ability of the superior pilot or aircraft to maintain the "tracking solution" differs. These differences between the Combat Hassle engagements and those simulated by TACTICS-II are most likely due to man-machine interactions rather than the failure of the computer model to adequately simulate the aircraft's capabilities. As indicated earlier, no attempt has thus far been made to build pilot capabilities and limitations into the TACTICS-II model; therefore, some differences in results are expected, especially those that can be attributed to differences in pilot skills.

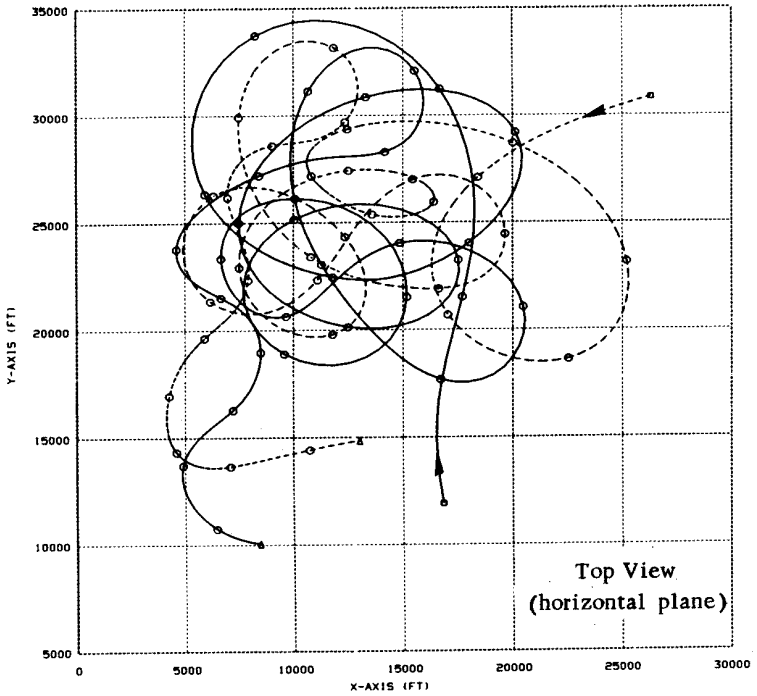


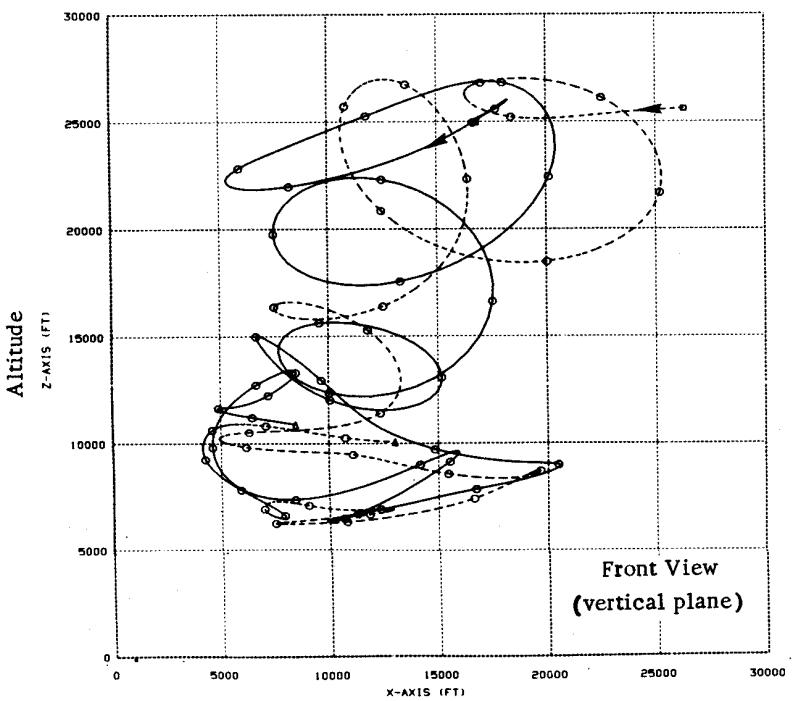
Fig. 10 — Typical Combat Hassle engagement: full afterburner versus 1/3 afterburner

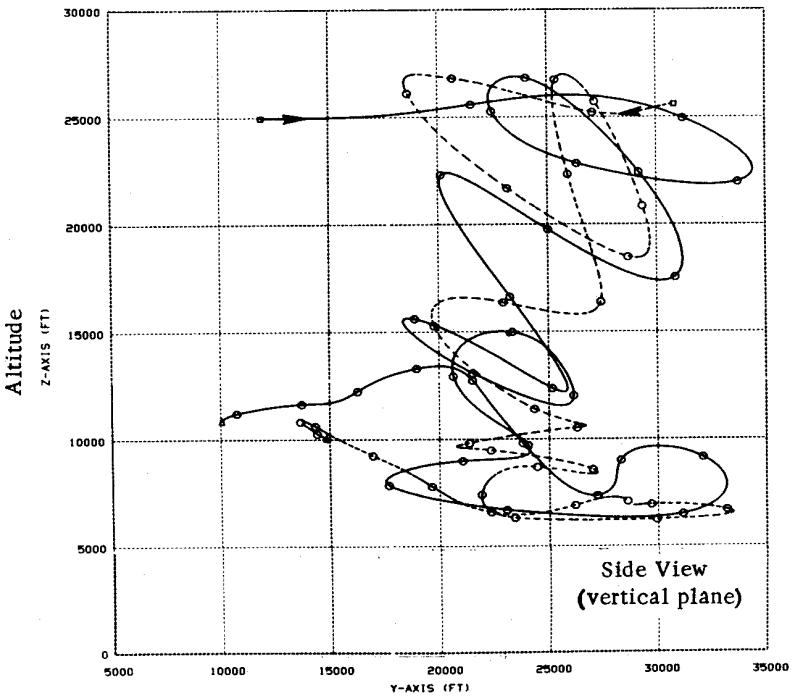
NOMINAL INITIAL CONDITIONS:

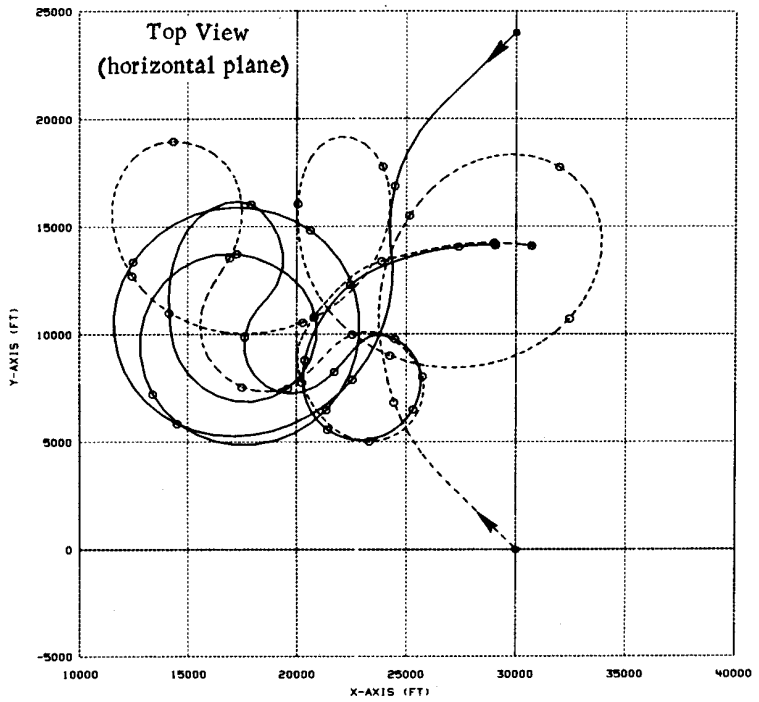
Altitude = 25,000 ft
Mach = 0.85
Range = 24,000 ft

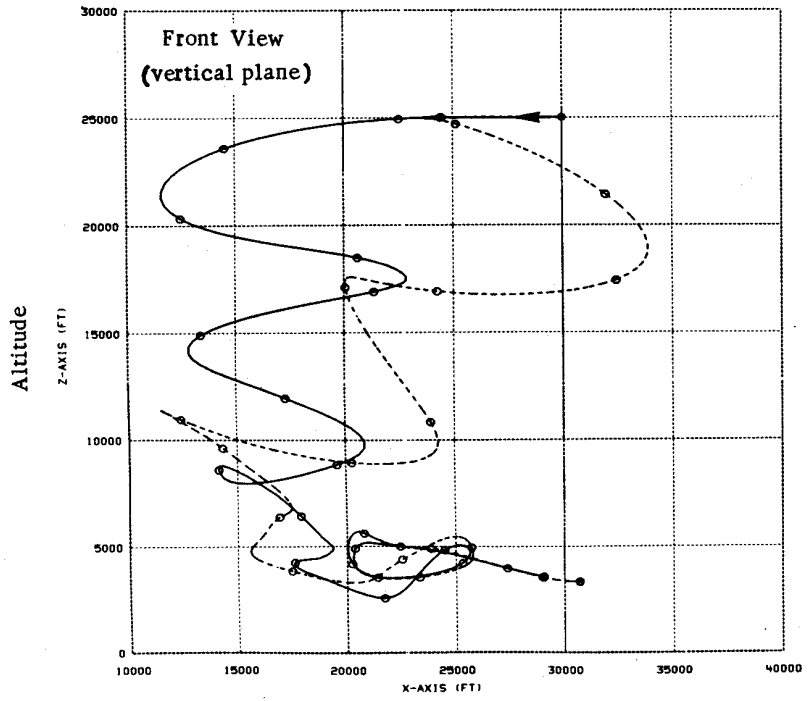
LEGEND:

——— Aircraft with full afterburner capability
----- Aircraft limited to 1/3 afterburner
□ Beginning of engagement
○ 10-sec time intervals
△ End of engagement









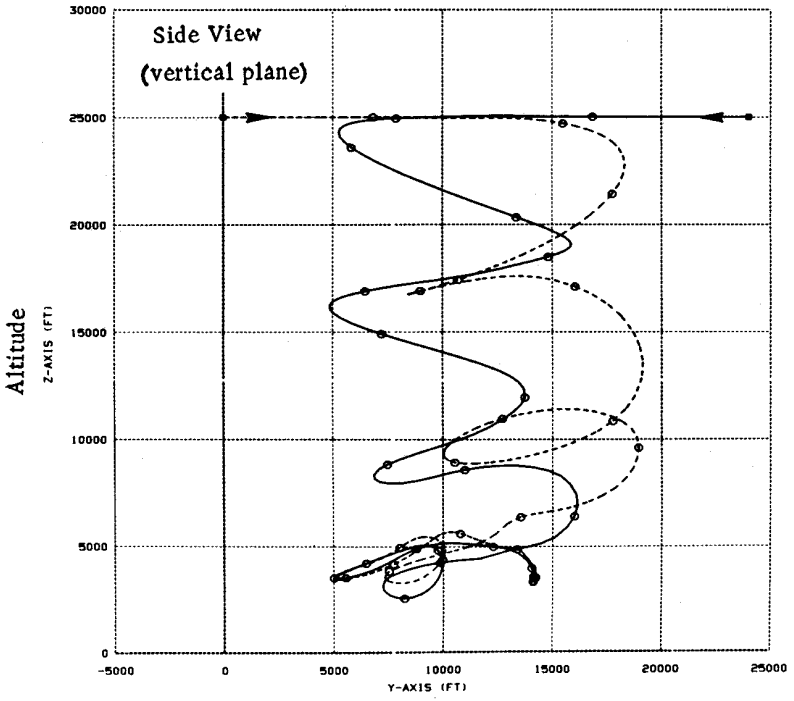


Fig. 11 — Tactics-II simulation: full afterburner versus 1/3 afterburner

INITIAL CONDITIONS:

Altitude = 25,000 ft
Mach = 0.85
Range = 24,000 ft

LEGEND:

——— Aircraft with full afterburner capability
– – – – Aircraft limited to 1/3 afterburner
□ Beginning of engagement
○ 10-sec time intervals
△ End of engagement

Conversion Time Comparisons

As defined by ADTC for analysis of the Combat Hassle results, the criteria for conversion were that the range between aircraft be less than or equal to 3000 ft, and that the pipper of the lead-computing optical gun sight be on the target for at least 0.5 sec. The relative range was determined from the smoothed radar positional data, and the "pipper-on-target" results were obtained from the gun-sight camera film.†

Table 1 compares the time-to-convert for the Combat Hassle engagements and some corresponding TACTICS-II simulations. These engagements have been divided into four categories, according to the maximum thrust capability of the combatants. The figures associated with the Combat Hassle mock dogfights represent the range of conversion times for the superior aircraft. The middle, underscored value for each group gives the mean or average time-to-convert; the parenthetical number in this column is the percent of engagements of each type in which the aircraft with the thrust advantage obtained a conversion.‡

A comparison of these values shows that the variation in conversion times for each type of engagement is quite large and appears to be nearly independent of the relative thrust capabilities of the two aircraft. On the other hand, the percent of conversions shows a strong effect of the relative aircraft capabilities; as the thrust advantage for one aircraft increases, the percentage of the engagements it wins increases markedly from 20 percent with no advantage, to nearly 80 percent in the case of full afterburner versus military power (a thrust advantage of about 2 to 1). Note, however, that conversions occurred in about 20 percent of the engagements in which neither aircraft had a thrust advantage. Furthermore, even in encounters in which one aircraft had a considerable thrust-to-weight advantage, the superior aircraft did

† Whenever a pilot had a firing opportunity and began to "fire," simulating a gun-firing pass, a gun-sight camera recorded the firing pass as seen by the pilot through the combining glass.

‡ Of the 82 Combat Hassle engagements, 10 consisted of full afterburner versus full afterburner. Of the remaining 72, there were only 3 engagements in which the lower-thrust aircraft was able to "win," and these were most likely due to the pilot's loss of visual contact or error.

Table 1

COMPARISON OF TIMES-TO-CONVERT FOR SUPERIOR AIRCRAFT

(sec)

Type of Engagements	Combat Hassle Mock Dogfights[a]	TACTICS-II Simulations[b]	Incremental Aircraft Turn Capabilities[c]
Full afterburner versus military power	98-193-275 (79%)	105-133	90
Full afterburner versus 1/3 afterburner	116-207-290 (75%)	151-166	120
Full afterburner versus 2/3 afterburner	73-210-289 (54%)	291-217	240
Full afterburner versus full afterburner	197-223-243 (20%)	Never	Never

[a]The conversion criteria were that the pipper of the optical gunsight was on the opponent for at least 0.5 sec and the relative range ≤ 3000 ft. Underscored numbers denote mean time-to-convert; parenthetical numbers represent the percent of engagements in which superior aircraft converted.

[b]The conversion criteria were that the superior aircraft was tracking its opponent and the relative range ≤ 3000 ft. Two different initial conditions were used.

[c]Calculated conversion time based on average difference in turn rate between aircraft within each aircraft's high-turn-rate flight region.

not always win. In almost 20 percent of the engagements between the aircraft with full afterburner and military power, the combats ended essentially in a draw, at least in terms of the conversion criteria. This implies that individual differences in pilots, even those highly trained and experienced, can significantly affect the outcome of dogfights. The Combat Hassle results demonstrate that pilot differences alone could not prevent the superior aircraft from winning most of the engagements, but could affect the time required to win and minimize differences in aircraft performance.

The third column in Table 1 presents the time-to-convert results obtained from the TACTICS-II simulations. These values correspond to the time at which the "winning" aircraft was able to track the opponent from within the opponent's rear hemisphere at a relative range of less than 3000 ft. Two values of conversion time are given to indicate the effect of varying initial conditions. The first value corresponds to the nominal Combat Hassle initial conditions; the second is the result of restricting the two aircraft to straight and level flight at their specified maximum thrust capabilities until the relative range between the aircraft decreases to about 3 nm, when both aircraft commence maneuvering as directed by the dogfight logic. These latter "initial conditions" for starting to maneuver appear to be more representative of the actual initial phase of the Combat Hassle flight tests. The results of these simulated engagements show that, in engagements where one aircraft has a thrust advantage, the superior aircraft accomplishes the conversion in a matter of minutes. If the thrust advantage is great, as in the case of full afterburner versus military power, the superior aircraft wins quickly. Of course, as shown in the fourth category (both aircraft on full afterburner), since the TACTICS-II model is a deterministic model with essentially idential pilots and aircraft, neither aircraft can attain a dominant position with respect to the other.

Comparison of the Combat Hassle results with the TACTICS-II results shows that the simulated results fall well within the range of the actual conversion times, except for the fourth category; however, the average times do not agree particularly well. For the first two engagement categories, the TACTICS-II mean conversion times are less than those shown for Combat Hassle; but for the last two, the mean conversion times are greater. Both sets of results show the trend for mean conversion time with an aircraft thrust advantage; however, the values do differ. These variations are most likely attributable to individual differences in pilots. As discussed earlier, the incorporated dogfight logic was designed primarily around the performance characteristics of an aircraft, and does not account for factors such as the pilot's capabilities, loss of visual contact with the opponent aircraft, and pilot load factor/time limitations.

The last column in Table 1 gives the results of a rather simple calculation of conversion time based on the relative turn-rate capabilities of the two aircraft involved in each type of engagement, as determined from the appropriate turn capability diagrams. The values given were calculated by dividing the average difference in turn rate between the two aircraft (within each aircraft's high-turn-rate region) into the approximate gain in angular turn required by the superior aircraft to convert to gun pass off the opponent's tail--i.e., a 180 deg turn increment, assuming their initial pass is essentially nose-to-nose. This calculation shows, as do the TACTICS-II results, that in cases where one aircraft has a thrust advantage, the superior aircraft can win each engagement in a reasonably short time (less than 5 min). Furthermore, in engagements where the thrust advantage is nearly 2 to 1, the superior aircraft can win even more quickly and decisively.

CONCLUDING REMARKS

It appears, from the trajectories generated using the dogfight logic described here, that the TACTICS-II approach to simulating one-on-one, close-in, air-to-air combat does produce credible maneuvers and tactics. Given the appropriate starting conditions, the type and form of the simulated maneuvers agree well with actual Air Force basic fighter maneuvers. Moreover, the trajectories produced by the simulation of extended dogfights appear to resemble those of the Combat Hassle flight test dogfights very well, in both overall characteristics and the dynamics of the combat.

The conversion data obtained from Combat Hassle and the TACTICS-II simulations correspond reasonably well in terms of the general magnitudes of the times-to-convert and the trend of the mean conversion time as a function of thrust advantage, although the values of mean time-to-convert are not as close as one might wish. However, these differences in the precise correlation of mean times-to-convert can be attributed to loss of visual contact and other human factors that are not taken into account in the TACTICS-II dogfight logic. Nevertheless, an overall comparison of conversion results of Combat Hassle and TACTICS-II shows the same trends in terms of the relative degree of superiority

the aircraft with full afterburner has over the one with limited afterburner. The Combat Hassle data demonstrate that, as the thrust advantage increases, the percent of conversions increases markedly; the TACTICS-II results show that the time-to-convert decreases significantly and the engagements change from long, involved dogfights to relatively short, decisive combats.

In addition, the TACTICS-II dogfight logic has been used in other Rand studies to simulate one-on-one engagements between a number of current and proposed fighter aircraft. Comparative analyses of these results with those indicated by the aircraft performance and turn capabilities have been promising. It appears that the dogfight logic developed and incorporated in the Rand TACTICS-II computer model can simulate realistic basic maneuvers and prolonged dogfights, at least for fighter aircraft of current interest.

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This report has been cleared for open publication by Clay E. Thompson,Jr., Chief, Air Force Division, Directorate for Freedom of Information and Security Review on April 5, 1979. References to publications which may still be classified have been deleted.