Design for Air Combat

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A combination of air combat simulation and aircraft synthesis techniques is used to analyze problems such as missile vs aircraft maneuverability, offensive vs defensive capability and the cost effectiveness of increasing energy maneuverability, e.g., quality vs quantity in air-to-air combat. Aircraft design parameter combinations ranging from 0.5 to 1.7 thrust/eight ratios, 40–90 lb/ft² wing loading and 1.2 to 2.4 maximum Mach number for fixed and rubberized engines are evaluated in combat environments. The results substantiate earlier findings such as the importance of turn performance at subsonic speeds. New insight is gained into the problems of detection and low level interception and into the behavior of a fleet of air superiority fighters.

I. Introduction

THE ability of a fighter aircraft to engage and kill another fighter aircraft in the air depends upon its maneuverability relative to the maneuverability of the opponent, e.g., on its ability to turn, to accelerate and to climb. The initiation of such an engagement depends on the ability to detect and to identify an air target and the capability to perform an intercept maneuver against an evasive or not reacting opponent. For proper balance of the design parameters which dictate the performance in the individual elements of air combat a common denominator is required. This denominator can be derived by air combat simulations which measure the capability of an aircraft design against a particular threat in terms of kills, survival or other relevant quantities. But even with this background the question remains to be answered how much maneuverability should be designed into a new fighter in view of cost penalties for increased performance. The answer to this question obviously depends upon the threat in terms of number and combat capability of hostile fighter aircraft.

In the work leading to this paper an attempt has been made to develop a generally applicable rationale for fighter aircraft requirements, primarily with respect to two important and cost driving parameters, thrust/eight and wing loading, in an iterative three step approach: 1) Parametric assessment of weight, size, production and operating cost of fighter aircraft as a function of maneuver performance by variation of T/W and W/S at constant range performance and given military equipment. This variation has been conducted by means of computerized aircraft synthesis (Ref. 1). 2) Parametric assessment of air combat capability in terms of a) probability to detect an air target under various environmental conditions, b) probability to perform a successful intercept from various positions, and c) probability to kill the opponent in a close-in combat. This assessment was made using computer simulation techniques for each of the above mission elements. 3) parametric assessment of the fighter fleet effectiveness against a fleet of enemy fighters in terms of the ratio of aircraft loss rates during a military conflict. This fleet deterioration has been calculated by application of suitable Lancaster equations[2] and a computerized war game.

Points 2 and 3 are, in this paper, completely covered only for the battlefield air superiority role, in particular the combat air patrol mission. Section 2 of this paper describes some weight-cost performance relationships derived from the systematic variation of important design parameters, such as wing loading, wing shape and thrust to weight ratio. Computations were based on state of the art rubberized engines. Design parameter values range from 0.5 to 1.7 thrust to weight ratio, 40–90 lb/ft² wing loading and 1.2–2.4 max Mach number.

A large group of consistent parametric fighter designs has been evaluated in a sequence of detection, intercept and close-in combat. Some of the relevant system parameter combinations and their impact on these three phases of air-to-air combat are discussed in Sec. 3.

Fighter designs with parameter combinations which achieve maximum individual combat results at a given level of system cost are discussed in Sec. 4. The effectiveness of these fighter designs has been analyzed in a fleet environment under constant budget cost. It is shown that an optimum combination of thrust/weight and wing loading can be found for a defined scenario. The concluding section tries to answer some of the questions which are vital in the design for air combat: 1) Can missile maneuverability compensate for lack of air vehicle maneuverability? 2) Are requirements for offensive and defensive com-

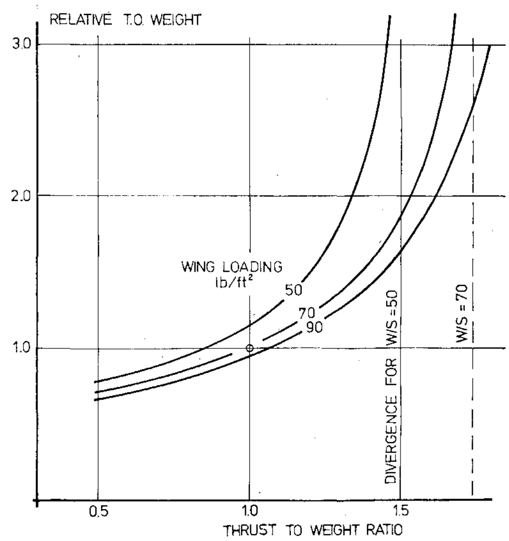

Fig. 1 Weight penalty of thrust to weight ratio and asymptotic performance limits.

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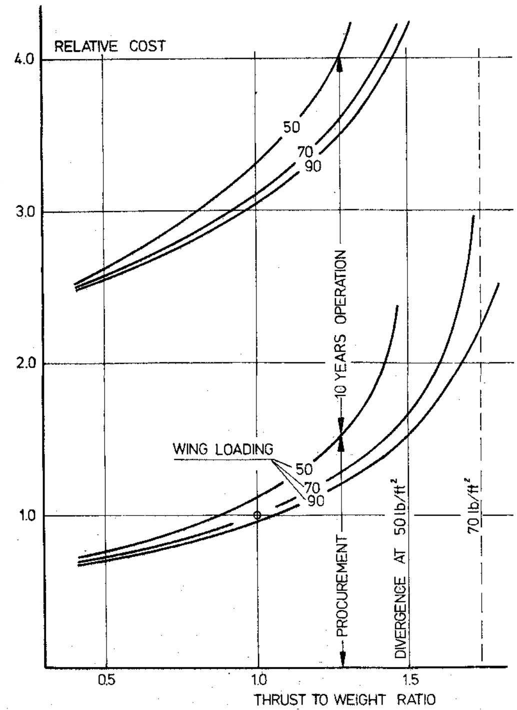

Fig. 2 Cost penalties of thrust to weight ratio.

bat capability different? 3) Is the SEP concept the key to superior combat performance? 4) How does the trend and the escalation to higher thrust-weight ratios look from a cost-effectiveness point of view?

II. Weight and Cost of Fighter Performance

The most powerful design parameters which affect the air combat capability for a given avionics and air-to-air weapon equipment are wing loading and thrust to weight ratio at combat conditions. Weight and cost increments for varying levels of T/W and W/S are shown. The specific excess power levels achievable through variation of these parameters are discussed and optimum T/W and W/S combinations for max SEP performance at given weight levels are derived. The weight penalties of increasing supersonic SEP performance and maximum Mach number at constant T/W and W/S conclude this section.

Weight and Cost for Various T/W and W/S Level

Figure 1 shows *T.O.* weight as a result of increasing T/W for various *T.O.* wing loadings. A T/W of 1.0 has

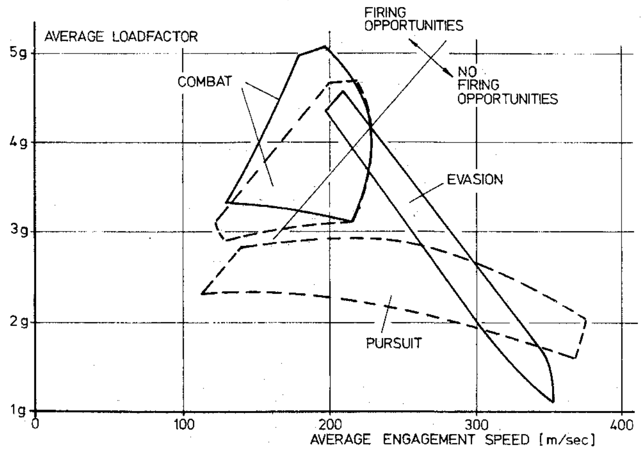

Fig. 3 Average speeds and loadfactor in simulated air combat.

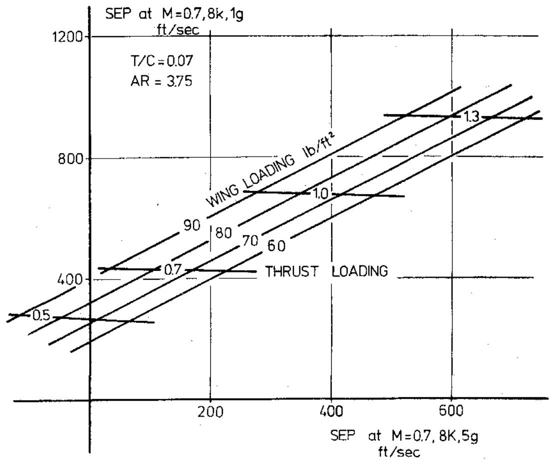

Fig. 4 Subsonic dash performance vs subsonic turn performance tradeoff.

been chosen as a point of reference to normalize the weight axis. The most important message of this analysis is that for a given engine technology, range and fixed equipment the *T.O.* weight approaches asymptotic limits of T/W for any given W/S. For example, the design of a fighter with a $T/W = 1.6$ and a $W/S = 50$ lb/ft² is currently beyond the state of the art. The design iteration process diverges at a $T/W = 1.5$ for the given set of requirements. The analysis is based on an air superiority mission radius of 150 naut miles. The weights which are not subject to aircraft growth such as military equipment, pilot, etc., amount to 23% of the reference aircraft *T.O.* weight. (See Ref. 3 for the rationale of such asymptotic performance limits.)

The weight and size characteristics of that field of parametric fighter aircraft are translated into procurement cost and operational cost in Fig. 2.

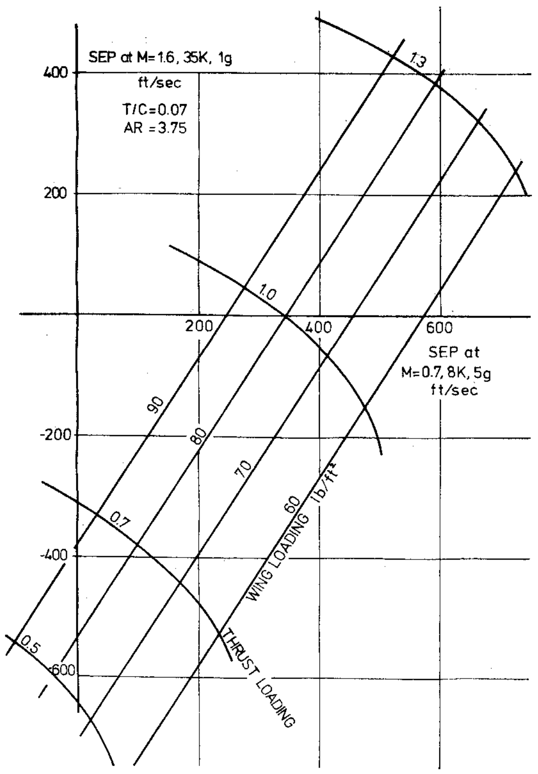

Fig. 5 Supersonic dash performance vs subsonic performance tradeoff.

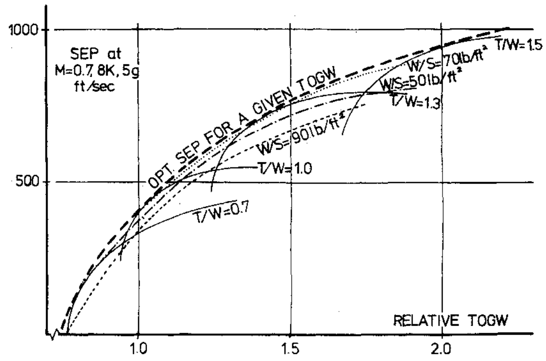

Fig. 6 Max SEP allocation vs TOGW.

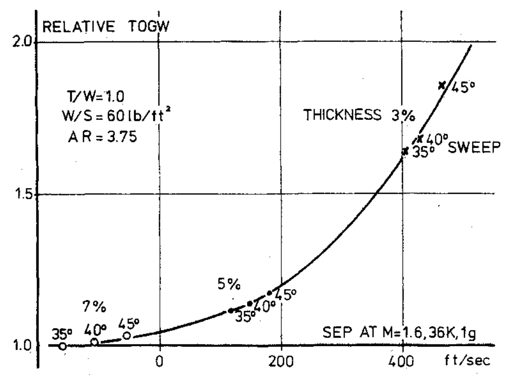

Fig. 8 Penalty of supersonic dash capability at constant close combat capability.

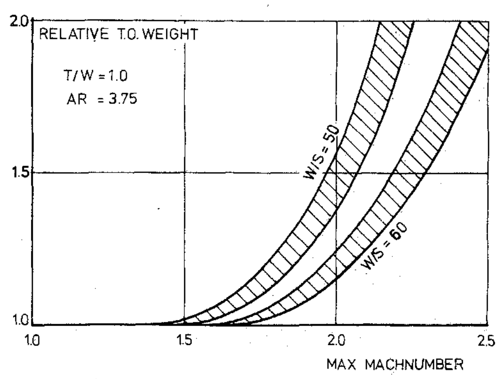

Fig. 9 Penalty of M_{max} at constant close combat capability.

Specific Excess Power

Specific excess power has been used as one design criterion at various combinations of speed and load factors. From flight experience and computer combat simulations high subsonic speeds and moderate load factors are generally accepted to be typical for air combat maneuvers. Figure 3 shows the average v/n combinations over a series of combat simulations for various fighter layouts against a MIG 21 type aircraft. $M = 0.7/4$ g seems to be a representative combination relatively independant of the particular design.

Figure 4 represents SEP-performance at 0, 7 air combat Mach number and trades dash performance (1 g) vs turn performance (5 g) at 8000 ft. There is little penalty to 1 g-performance as W/S decreases at constant T/W in order to achieve better 5 g turn performance. This relation is important to know in order to understand the trends in the combat capability plots presented later in this section. However, supersonic dash capability suffers with increasing subsonic turn performance at constant T/W as shown in Fig. 5.

Figure 6 represents an allocation of T/W and W/S for maximum SEP at $M = 0.7$, 5 g at any given $T.O.$ weight. The line of optimum SEP values is the envelope of the SEP values for all possible T/W and W/S combinations plotted over their corresponding $T.O.$ weight. The figure is a cross plot of Figs. 1 and 4. The corresponding optimum values of T/W and W/S are plotted in Fig. 7. This fundamental relationship will be compared later with the resulting optimum T/W and W/S combinations of the air combat evaluation, which are derived in the following section.

Weight Penalties for Supersonic Design

In the design synthesis supersonic performance has been treated as a fallout of the optimization for sub/transonic combat performance. Improved supersonic performance at constant sub/transonic performance requires a different wing and inlet design resulting in a $T.O.$ weight penalty.

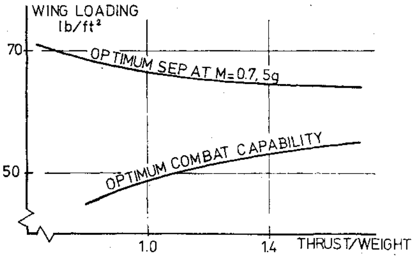

Fig. 7 Optimum combination of design parameters.

This is shown in Figs. 8 and 9 at constant T/W and W/S. In the following evaluation such an improvement in supersonic performance shows up as a cost penalty only, without significant enhancement of air combat capability, when the fighter aircraft operates in a combat air patrol mode. However, increased supersonic performance can be desirable for point intercept maneuvers with ground control and guidance, as well as fighter escort missions. Both are not considered in this paper.

III. Elements of Air Combat Capability

The major elements of an air combat mission and the system parameters which drive the capability in these elements are discussed. The quantitative relations in the three considered mission parts, detection, intercept, and combat maneuver/weapon release shown here were derived for a Barrier Combat Air Patrol (BARCAP) over the battle area in a mid 1980's European scenario. Prime ob-

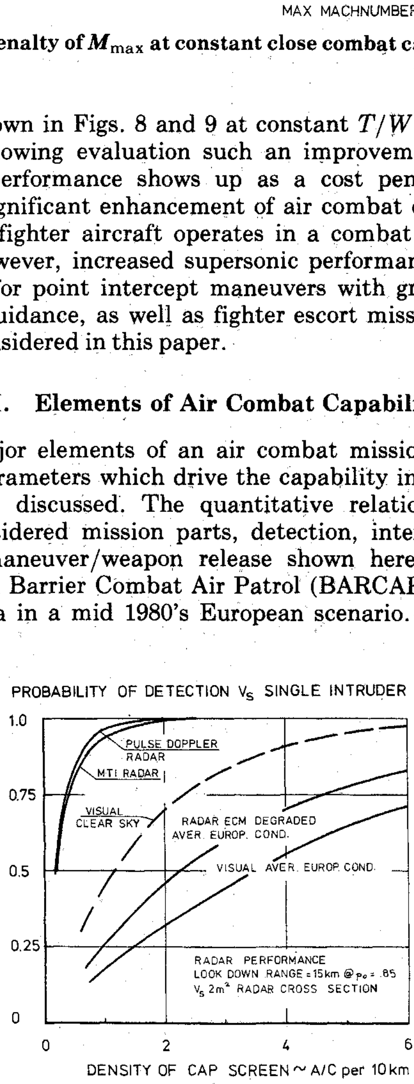

Fig. 10 Combat air patrol detection of low level intruders.

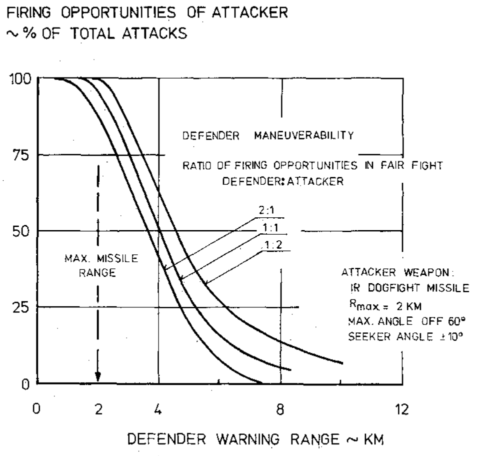

Fig. 11 Impact of tail warning range on rear hemisphere attacks.

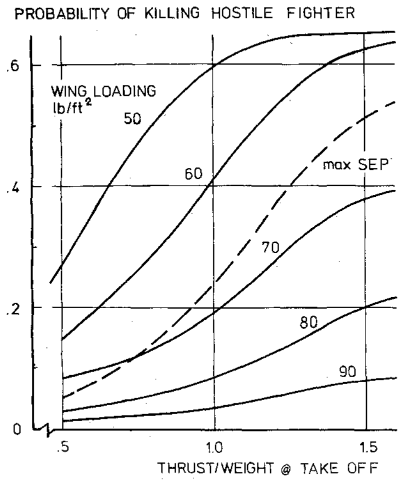

Fig. 13 Air combat vs standard A/C, $W/S = 70$, $T/W = 0.7$.

jective is to deal with low flying hostile fighter bombers which are protected by fighter escorts.

Detection

Probability of airborne target detection is primarily an equipment problem. However, the number of available CAP aircraft has an impact on detection capability, as shown in Fig. 10 (under a constant budget constraint that number will be lower for higher performance aircraft). Figure 10 is a result of simulations and shows detection probabilities of Puls Doppler Radar and Moving Target Indication Radar as well as visual capabilities for varying numbers of CAP aircraft. The simulation includes the weighted effects of various aircraft positions and headings in a combat air patrol environment. Obviously, an intercepting fighter can fully utilize a better acceleration capability only with a matching performance of his searching device. For the purposes of this paper, however, it is assumed that there is no detection problem in order to avoid radar equipment cost and performance considerations. Therefore detection probability is set to the value of one.

Just to pursue the problem of detection a little further, the capability of an intruder to realize (by means of a rearward warning device) that he is attacked from the rear is considered in Fig. 11. Computer simulations show that the opportunity of the attacking aircraft to get into a firing position with an A-A missile becomes rare as the rearward detection range of the attacked aircraft is improved, and it can take appropriate action in time. Rearward warning seems to be an effective tactic for defense.

Intercept

The intercept of an aircraft penetrating a CAP screen starts at various conditions of initial range and lead or lag angle to the target. These conditions have been simulated in a CAP intercept model. The success/failure of the intercept maneuvers from the weighted starting positions are shown vs target escape speed,‡ fighter acceleration and dash speed capability in Fig. 12. Fighter thrust to weight ratio proved to be the driving design parameter since wing parameters do not have a significant impact on the 1 g accelleration capability in the subsonic region as has been demonstrated in Fig. 4.

Close-In-Combat

After a successful intercept maneuver both aircraft try to achieve a firing position or to neutralize an initial position advantage of the opponent. The task of achieving or avoiding a firing position is considerably influenced by enlarged weapon envelopes of IR missiles. The question of supplementing or replacing air vehicle maneuverability with weapon maneuverability will be discussed after the analysis of aircraft maneuverability with equal and fixed weapon capabilities.

Air Vehicle Maneuverability

Figures 13 and 14 pertain to the last phase of the combat maneuver in which both opponents are trying to get into a tail end firing position or to escape from such a position, respectively, by means of performing optimum maneuvers of subsequently accelerating, decelerating, climbing, descending and turning. The ability to perform these maneuvers is constrained by the energy maneuverability

‡It is assumed in these simulations that the target tries to continue on its heading at max speed until the attacker is so close that the target has to abort its mission and start defensive maneuvers. This constitutes a successful intercept.

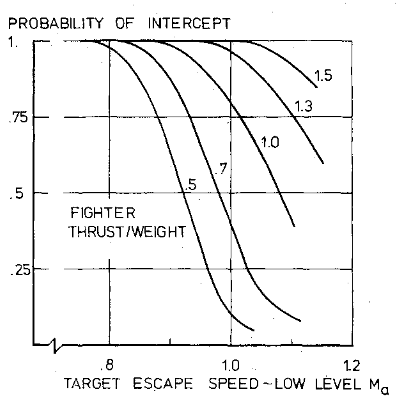

Fig. 12 Intercept of evading opponent.

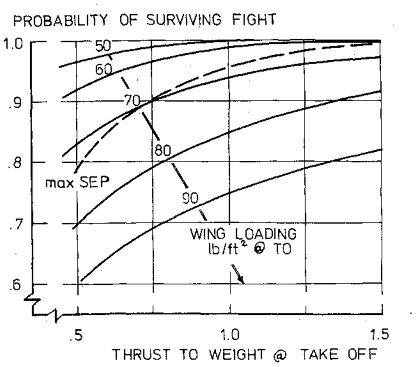

Fig. 14 Air combat vs standard A/C, $W/S = 70$, $T/W = 0.7$.

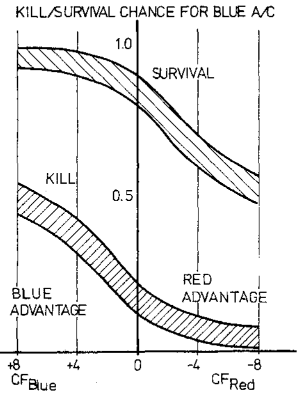

Fig. 15 Correlation of design parameters with close in combat performance.

and instanteneous load factor capability of the air vehicle, by its structural strength and by the physical limitations of the pilot.

Plotted are the chances of kill and survival which an aircraft with thrust/weight ratio and wing loading combinations can achieve against a fixed opponent. The opponent is a member of the parametric family of fighter designs described in Sec. 2. It has a T/W ratio of 0.7 and a wing loading of 70 lb/ft^2. Results are averages of a large series of dogfights with starting positions for each pair of opponents. The weapon envelope is that of a current state of the art short range missile. Figures 13 and 14 distinguish between the probability to kill and the probability to survive. Kill success depends much more on T/W than the chance to survive. Both criteria are more sensitive to W/S than to T/W. From Figure 7 the optimum SEP-correlation has been transfered into Figs. 13 and 14. This shows a design for maximum SEP even at the most relevant fight conditions does not neccessarily coincide with a choice of T/W and W/S which yields maximum combat capability. This statement will be further substantiated later.

Although T/W and W/S are the most important design parameters, the effect of other wing and engine characteristics should not be neglected. The most sizing engine parameter is the bypass-ratio. It affects SFC and combat T/W at a given takeoff T/W. SFC has just a scaling influence on weight and cost, and T/W is parametrically varied anyway. In this paper, thereforè, a variation of engine characteristics is not discussed. However, some important wing design parameters, aspect ratio AR, average wing thickness t/c and leading edge sweep angle φ are considered. A large number of combinations of these wing parameters in conjunction with the variation of T/W and W/S has been analyzed in terms of the resulting performance (design synthesis model) and combat capability (dog fight model) against a number of opponents. The results scatter somewhat and are therefore plotted as bands

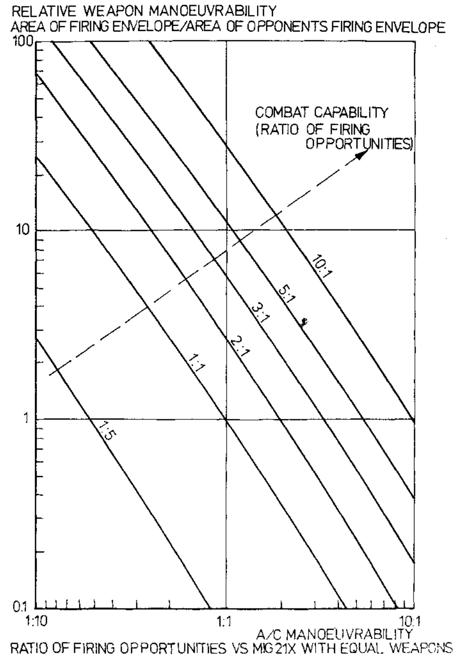

Fig. 17 Missile vs air vehicle maneuverability tradeoff.

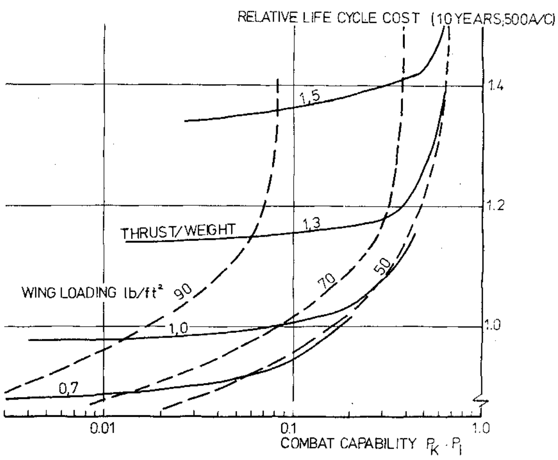

Fig. 18 Cost penalty of increased combat capability.

in Fig. 15 in terms of the statistical chance to survive against an opponent or to kill that opponent. The maneuverability of both opponents is expressed as a correlation factor CF which is a function of the investigated design parameters:

$$CF = 5(AR + 100\,t/c + 10\,\cos\varphi)^{1/2} + 10(T/W)^{1/2}$$

$$- 0.2\,W/S + 1.5\,MD \times AR \quad (W/S \text{ in lb/ft}^{1/2})$$

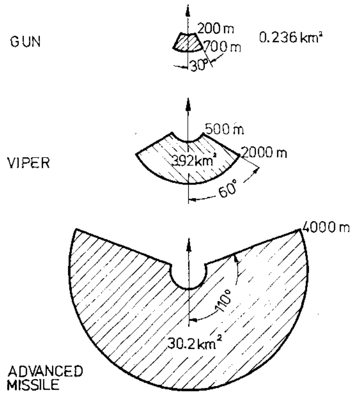

Fig. 16 Weapon envelopes.

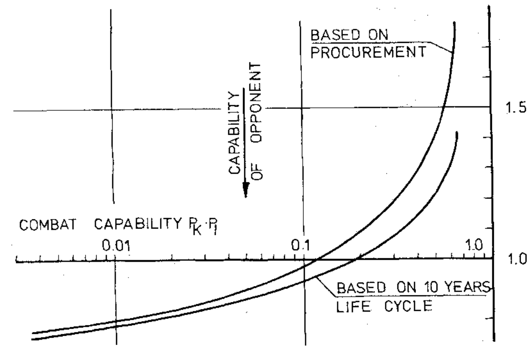

Fig. 19 Minimum cost penalty of combat capability.

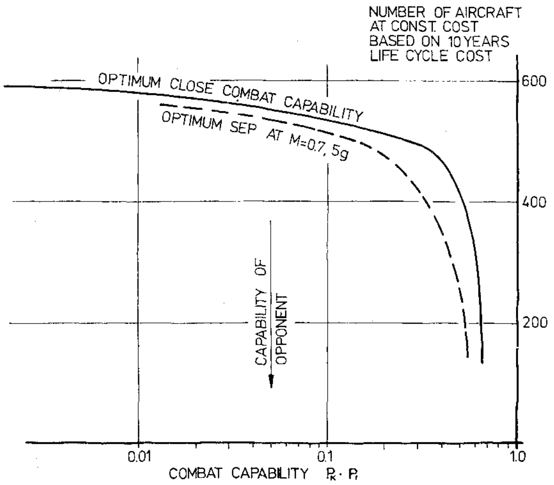

Fig. 20 Quantity vs combat capability (quality) tradeoff.

MD is a control symbol for maneuvering devices having the value of either one or zero. The differences of the correlation factors

$$\Delta CF_1 = CF_1 - CF_2 \text{ and } \Delta CF_2 = CF_2 - CF_1$$

show for each opponent its approximate chances of kill and survival against each other.

An analysis of this correlation quantifies the importance of wing loading as compared to other design parameters. A similar investigation of maneuver devices indicated the usefullness of such devices even if they are causing a weight increase and a deterioration of SEP performance. The overriding effectiveness of turn rate pertains to both an aggressor aircraft as well as an aircraft which has just the intention to survive. The simulations demonstrate that running away is a more dangerous tactic even for an aircraft which is designed for superior longitudinal accelleration. Turning proved to be the best defense, since the place behind the opponents tail is (still) the safest.

Weapon Maneuverability

Thus far we have considered the air vehicle maneuverability only. The simulations were based on short range air-to-air missiles of equal maneuverability. An increase of missile maneuverability would improve the aggressive capability of kill. However, would it allow to relax the maneuverability of the air vehicle and thus allow to lower the cost of the weapon system at constant weapon system effectiveness?

Relative weapon maneuverability was expressed as the ratio of the areas behind the target in which the weapons considered can be successfully launched. These envelope areas are shown in Fig. 16 for a VIPER type missile as compared to a gun and to an assumed advanced missile of the 1980's. In Fig. 17 air vehicle maneuverability is expressed in terms of close combat exchange rates and plotted against relative weapon maneuverability. The parametric lines describe the resultant combat capability of the combined system air vehicle and weapon. The engagement of equal opponents (aircraft maneuverability 1:1) with equal weapons (relative weapon maneuverability = 1) results in a ratio of firing opportunities equal to one. A weapon improvement by a factor of 10 increases the system combat capability only by a factor of 5.

Improved weapon maneuverability pays off only to a limited extent because a superior missile is of little use in a defensive combat situation. Air vehicle maneuverability

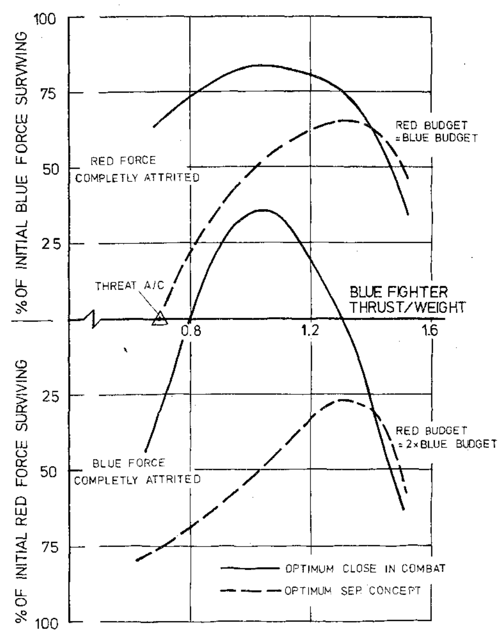

Fig. 21 Optimum design vs defined threat.

is still required to neutralize a position advantage of the opponent.

IV. Optimum Fighters for Close-In Air Combat

The relation of design parameters and cost (Fig. 2) and the translation of these design parameters into combat capabilities has been developed in the previous section (Figs. 12–14). Thus combat capabilities and the cost to achieve this capability can be computed. It seems reasonable to express the total combat capability as the product of the probabilities of detection, interception and close-in combat because they are subsequent maneuvers.

Figure 18 shows the life cycle cost for a fleet of 500 aircraft operating over 10 years peace time for the various combinations of T/W and W/S against that capability product, the probability of detection assumed to be equal to 1. Because of the asymptotic characteristics of T/W for particular wing loadings it happens that the parameter field can not exceed an asymptotic envelope, which is plotted in Fig. 19. This envelope represents aircraft layouts with combinations of T/W and W/S which yield a maximum combat capability at a given cost or a minimum cost at a given combat capability respectively. This is the line of optimum designs for air combat. These optimum combinations of T/W and W/S are plotted into Fig. 7 for comparison with the optimum SEP concept combinations. The two criteria result in different aircraft layouts. In particular, the level of wing loading is considerably different. At equal thrust/weight ratios the SEP concept with its higher wing loading yields lighter and consequently cheaper aircraft at the penalty of decreased close in combat performance.

Quantity vs Quality

Each combination of T/W and W/S on the envelope in Fig. 19 or on the lower line in Fig. 7 represents a relative optimum for a particular budget in terms of total life cycle cost an air force is willing to spend for a fleet of 500 fighter aircraft. That air force may, however, procure and operate a smaller number of more capable aircraft or a larger number of less capable aircraft for the same cost. Under such alternative policies each individual aircraft may still be an optimum fighter for its price as long as its combination of T/W and W/S corresponds to the optimum line in Fig. 7. In Fig. 20 total life cycle cost of 500 reference aircraft is conversed into numbers of less capable and more capable optimum aircraft. This calculation considers the specific cost reductions of a larger quantity production and operation and the specific cost penalties of a smaller quantity respectively. Of course, the same thought can be applied to a series of aircraft designs which are optimized for maximum SEP according to the upper line in Fig. 7. The resulting quantity-quality line is also plotted into Fig. 20 for comparison. Obviously, the choice of a particular design on this quantity-quality trade curve is a matter of the total fleet effectiveness and subject to the number, individual capability and the mode of operation of the enemy aircraft, e.g., it is a matter of what can be called fleet effectiveness.

A number of alternative fleet concepts have been investigated by means of a computerized war game. This "Fleet mix model" simulates the interaction of two opposing fleets with variable numbers and capabilities of aircraft for all combat functions considered in the defined scenario. Fleet deterioration and impact on the land battle are computed. The results show the importance of aircraft numbers for an optimum fleet allocation. In a simplified manner this fact is explained by the Lancaster theory (Ref. 2). Our example involves only the interaction of a fleet of attackers and defenders. The trends of the resulting fleet deterioration on which Fig. 21 is based have been verified by the use of the appropriate Lancaster equations.

The figure shows the effectiveness of different blue fleets against two different red threats. Effectiveness is the percentage of surviving blue aircraft after all red aircraft are attrited (or vice versa). The horizontal axis represents blue aircraft quality in terms of T/W. Each curve in this figure is computed for equal blue cost. Consequently the blue fleet size decreases as T/W increases according to Fig. 20. The solid lines represent fleets of aircraft designed to an optimum combat capability wing loading. The dashed lines relate to the optimum SEP concept. The lower and upper solid and dashed lines are computed for two multiples of red to blue fleet cost and thus for different ratios of fleet sizes.

The assumed red aircraft capability is about that of current fighter aircraft. It seems to be cost effective to operate superior and even more expensive blue aircraft up to T/W values of about 1.0 against such red opponents. Aircraft designed for optimum SEP require higher T/W values to achieve their optimum fleet effectiveness, however, the level of fleet effectiveness suffers from the lesser combat capability. Values of T/W beyond the optimum result in a deterioration of fleet effectiveness due to the progressively rising cost of individual aircraft.

A more advanced red aircraft would shift the point of optimum fleet effectiveness to even higher values of blue aircraft performance. However, there is a point where further increase of red performance makes it cheaper to achieve superiority through numbers rather than quality.

Summary

Increasing thrust/weight and decreasing wing loading has a progressive effect on weight and cost. This leads to combinations of T/W and W/S which can not be realized with the present state of technology. Design for optimum combat capability disagrees with the SEP concept. Optimum combat capability yields lower wing loading, particulary at moderate T/W ratios. Better missile maneuverability allows to relax air vehicle maneuverability only to a limited extent, if decreased aircraft survivability is acceptable. Defensive capability—as opposed to offensive capability—calls for lower wing loading rather than higher thrust to weight ratio. Current threat aircraft performance justifies the development of significantly superior fighter aircraft.

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