Dynamics of Air Combat

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New short- and medium-range air-to-air weapons have been analyzed by means of computerized and manned air combat simulation. As a result of their peculiar capabilities, air combat maneuver characteristics are expected to change significantly. The all-aspect capability of new short-range weapons leads to a dominance of head-on engagements and thus to an increase of importance of instantaneous maneuver capability over the classical sustained performance. Typical flight conditions are analyzed in terms of turn rates, rates of climb and rates of longitudinal acceleration and in terms of the resulting power and energy management. The guidance and performance capabilities of new medium-range weapons lead to a maneuvering-type combat in the supersonic speed regime. Typical flight conditions and power/energy management characteristics of medium range air combat engagements are analyzed similar to short-range combat and mutually compared. Finally, the impact on fighter design requirements is discussed.

Nomenclature

D	= level flight drag
E	= total energy
g	= gravity
h	= altitude
MR	= medium range
SR	= short range
t	= time
T	= propulsive thrust
V	= speed of flight
V_s	= sink/climb speed
W	= aircraft weight
ΔD	= drag increment due to turning
SEP	= specific excess power

Introduction

SIGNIFICANT changes in air combat characteristics will occur owing to the development of the following new air-to-air weapons and fire control systems: 1) all-aspect capability SR missiles; 2) all-aspect capability guns in conjunction with unorthodox aircraft maneuvers and coupled fire/flight control systems; and 3) new radar guided MR missiles.

How will these new weapon capabilities influence the combat characteristics and thus the design requirements of fighter aircraft, in particular the requirements for maneuverability?

The analysis of future air combat and fighter design requirements has been the subject of several years of work at MBB. The results are based on extensive computer combat modeling and on manned combat simulation[1] and even on flight testing.

SR combat with rear aspect weapons was characterized by sustained turns. Conversion to a firing solution was a matter of sustained turn rate margin vs the opponent. Combat effectiveness, therefore, tended to be very sensitive with regard to a variation of T/W and also to wing aspect ratio and wing loading. With all-aspect weapons,[2] however, combat effectiveness proves to be significantly less sensitive to classic energy maneuverability parameters and more sensitive to attained unsteady performance.

MR combat with semiactive radar guided missiles was assumed to be a standoff problem. Aircraft maneuverability was considered to be of minor importance and high speed was sometimes a penalty in a head-on situation against a similar armed target. Air combat modeling using the new generation of MR missiles indicates that combat effectiveness can be significantly improved if maneuvers at high supersonic speed are employed.

The change in SR combat characteristics toward unsteady maneuver performance in the low subsonic speed regime and the need for supersonic maneuverability in MR combat are contradicting design requirements. This presents a design challenge if both missions have to be satisfied with the same fighter aircraft.

Short-Range Air Combat Characteristics

The significant observation throughout a large number of simulated engagements with all-aspect weapons is the dominance of frontal firing opportunities. Figure 1 shows the frequency distribution of missile firing opportunities with respect to attack aspect angle. Predominantly, the most effective prelaunch maneuvering tends to lead to an almost head-on firing situation, independent of the initial condition (except tail-on initial conditions). There is a small difference between duels and multiple engagements. There is also an influence on actual missile hits; beam attacks tend to yield a smaller probability of target hits. Direct head-on passes happen rarely because of missile seeker characteristics and missile off-bore sight capability.

The ability to aim the aircraft fuselage independently of the flight path provides a very effective way of solving the gun snap shooting problem, and permits successful frontal hemisphere firing opportunities. Fuselage aiming—if properly designed and mechanized—makes the gun a very effective frontal hemisphere weapon and thus compatible with future missiles.

With all-aspect weapon capability there are no sanctuary spaces remaining around the target. There is a certain level of kill probability whenever the target is within range and within a certain off-bore sight cone. In this situation a pilot may not have a choice of maneuvering defensively or offensively. In many cases the only way to survive is to respond aggressively and to achieve an earlier firing opportunity. As a result, both opponents would engage in a sequence of head-on passes. After each pass, provided a mutual weapon exchange was unsuccessful, both aircraft would try to reverse as quickly as possible, even at the expense of energy. Any loss of energy could be replaced as appropriate later on.

Starting at high subsonic speed, it has been observed in many simulated engagements that SR combat develops in the following three phases:

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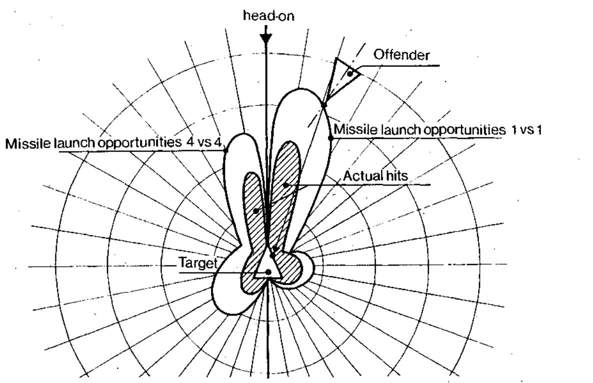

Fig. 1 Aspect angle frequency distribution of missile launch opportunities with all-aspect weapons in one vs one and four vs four SR air combat.

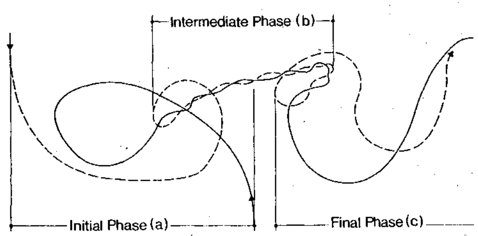

Fig. 2 Trajectories and phase development in simulated SR air combat.

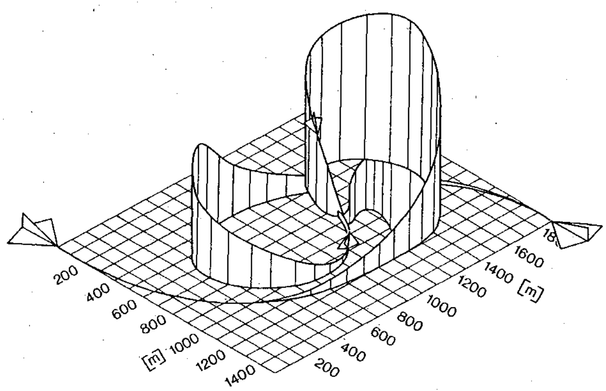

Fig. 3 Typical SR combat engagement with head-on weapons, initial phase a.

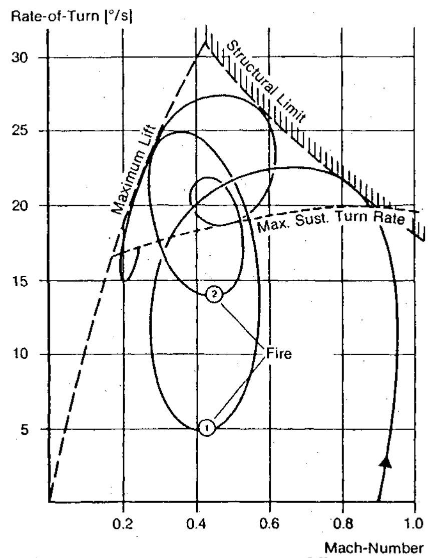

Fig. 4 Time history of maneuver conditions in simulated SR combat. Rate-of-turn vs speed interchange.

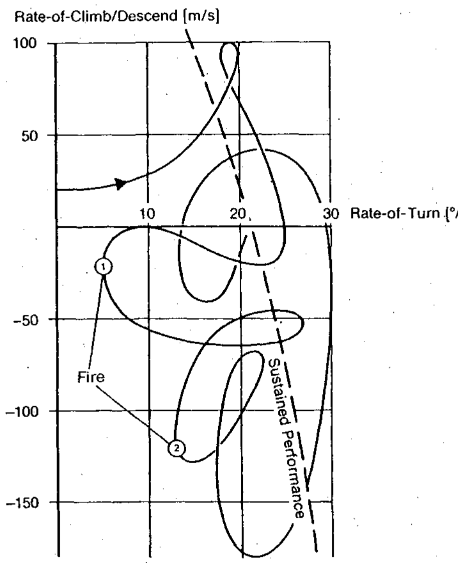

Fig. 5 Sequence of maneuver cycles in simulated SR combat. Rate-of-climb vs rate-of-turn interchange.

a) by slowing the aircraft into a better turning speed regime and thereby maneuvering into a head-on situation (this may be accomplished by gaining altitude, by throttling the engine, or by means of speed brakes, or by a combination of all three means);

b) by repetitively turning into each other at lower speed, with a possible loss of altitude; and

c) in proximity to the ground, by low-speed clinch or target pursuit depending on the outcome of phase b.

Figure 2 plots such a typical sequence of maneuvers during a continued combat engagement. Figures 5 and 6 present a special view of a typical SR combat maneuver for two different starting conditions.

Figures 4 and 5 plot a time history of maneuver conditions for one of the two opponents. Its most significant feature is the continuous change of flight conditions throughout the entire engagement and the repetition of a typical cycle with 1) conversion of kinetic energy into altitude (if possible) and a simultaneous buildup of turn rate; 2) loss of speed for even higher (instantaneous) turn rates; and 3) conversion into firing position at decreasing rate of turn and increasing speed. Firing position is achieved at a moderate rate of turn.

This typical cycle is basically independent of engagement phases a and b; however, the average flight condition (or level of energy) drifts to lower speeds and higher rates of descent. The rate of turn increases to take advantage of the potentially higher instantaneous (attained) turn rates close to, or at, maximum lift. In this example the angle of attack was limited to maximum lift. It has been demonstrated in computerized and manned combat simulation[1,2] that exceeding maximum lift (post-stall) constitutes a significant tactical advantage if sufficient control power is provided in all aircraft axes.

There is a line of maximum sustained turn capability (represented by the dashed lines in Figs. 4 and 5) above which energy is increasingly and intentionally given up for positional tactical advantage. That energy would have to be regained during the maneuver section below the dashed line.

Figure 6 plots a time history of firing opportunities in terms of aspect- and off-bore sight angles (relative to velocity vector). It shows the head-on characteristics typical of air combat with all-aspect weapons. In the end phase (c) of this particular example (about 65 s elapsed time) a tail chase develops.

Maneuver conditions result in a continuous interchange of energy states with varying power requirements.

1) Turning: excess thrust, T, is needed to compensate for higher induced drag, ΔD.

2) Climbing: excess power is needed for accumulation of

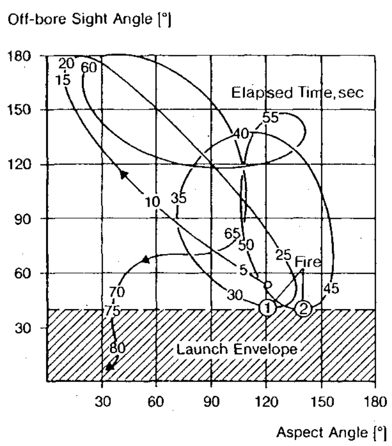

Fig. 6 Time history of fire conditions in simulated SR combat. Numbers represent elapsed time in seconds. Circled numbers represent firing opportunities.

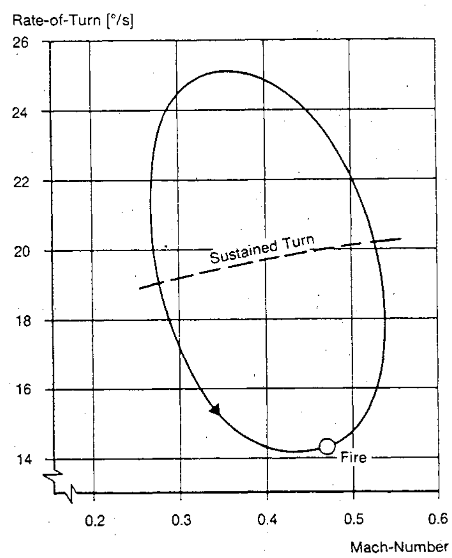

Fig. 7 Maneuver conditions in a typical SR combat maneuver cycle.

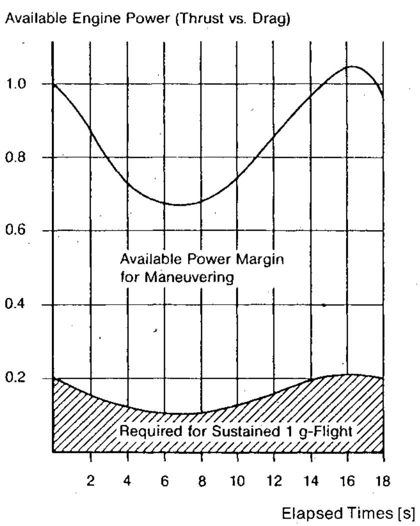

Fig. 8 Breakdown of available engine power, typical SR combat maneuver cycle.

potential energy. Altitude energy can be fed back into the system in descending flight, V_s.

3) Acceleration: excess thrust is needed for accumulation of kinetic energy which can be fed back into the system in decelerated flight.

Besides points 1-3 a certain amount of thrust is required to compensate for the basic drag D which develops at sustained $1g$ level flight. The required net thrust-to-weight ratio at any

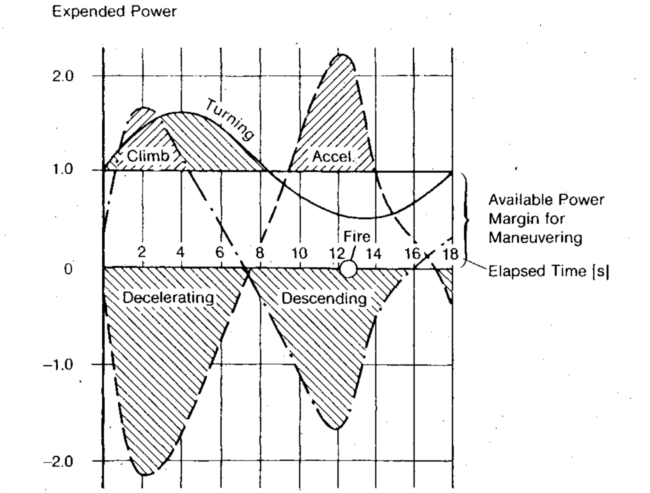

Fig. 9 Power management in a typical low-speed SR combat maneuver cycle.

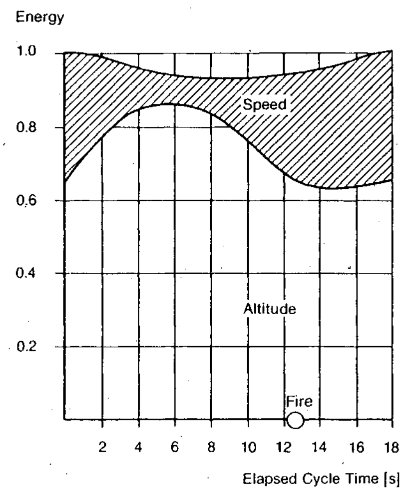

Fig. 10 Breakdown of energy status in a typical low-speed SR combat maneuver cycle.

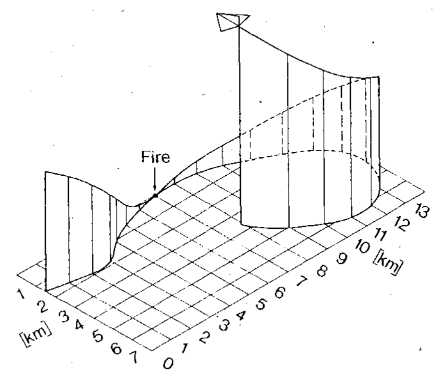

Fig. 11 Typical MR combat engagement.

point in time follows from

$$\frac{T}{W} = \frac{D}{W} + \frac{\Delta D}{W} + \frac{V_s}{V} + \frac{\mathrm{d}v}{\mathrm{d}t}\frac{1}{g} \tag{1}$$

Figure 7 represents a simplified closed-loop maneuver typical of future SR combat. Equation (1) is applied to this maneuver cycle for the analysis of important maneuver conditions. At each time throughout the maneuver cycle the amount of engine thrust is calculated which is available for maneuvering (Fig. 8).

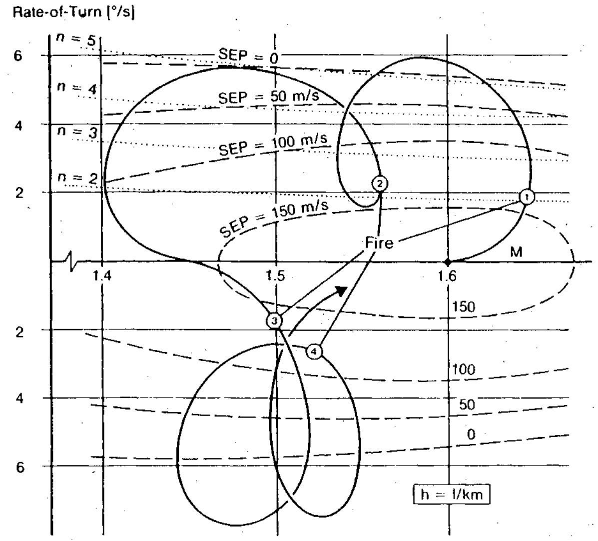

Fig. 12 Time history of maneuver conditions in simulated MR combat. Rate-of-turn vs speed interchange. SEP contours of a high-performance aircraft.

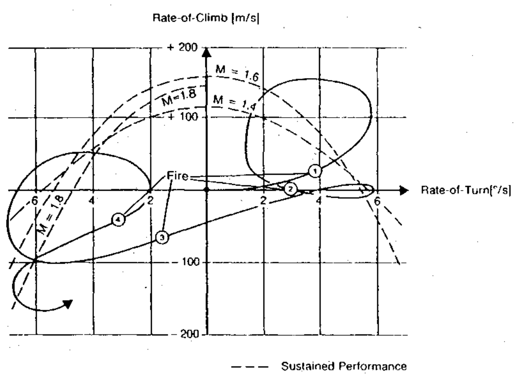

Fig. 13 Sequence of maneuver cycle in simulated MR combat. Rate-of-climb vs rate-of-turn interchange.

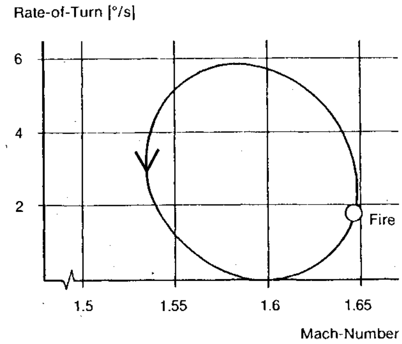

Fig. 14 Simplified typical MR combat maneuver cycle, accelerations.

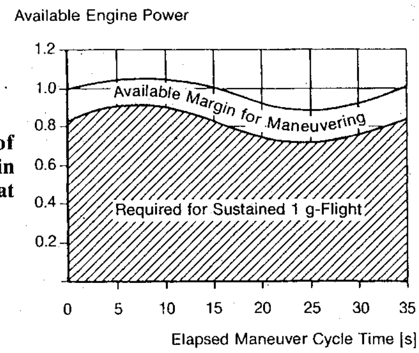

Fig. 15 Breakdown of available engine power in a typical MR combat maneuver cycle.

Typically in SR combat excess thrust is very large as compared to the thrust for level flight.

Figure 9 shows the time history of the maneuver elements of Eq. (1). It demonstrates the highly dynamic character of SR air combat with all-aspect weapons. Prior to weapon launch, the power expended for turning and climbing exceeds the available power by a significant margin. It must be compensated by a loss in speed. After weapon launch the need for turning power relaxes and kinetic energy is recovered by large sink rates.

At any elapsed time the state of energy can be determined by

$$E = V^2/2g + h \tag{2}$$

Energy throughout the maneuver cycle is calculated in Fig. 10. There is a continuous interchange of kinetic and potential energy. Some total energy is given up prior to weapon launch and recovered during the rest of the maneuver cycle.

Medium-Range Combat Characteristics

MR missiles are frontal hemisphere weapons by design and definition. In comparison with SR combat, firing ranges are much larger than aircraft radii of turn. Therefore fighter aircraft would not pass each other and would not reverse their position. However, they would employ very dynamic maneuvers in order 1) to achieve a firing position (with regard to aspect, speed, and altitude) which provides a target hit with a minimum counterhit probability; 2) to stay out of, or maneuver out of, the opponent's missile envelope after their own launch while maintaining the required look angle for midcourse guidance; and 3) to sustain sufficient energy after the initial combat maneuver for reattack and to continue fighting against other opponents in a multiple situation.

Of course, opponents would employ similar tactics. Thus a combat develops which is characterized by dynamic high-speed maneuvers in a relatively large airspace. Figure 11 shows a representative section of one of many simulated MR combat engagements. Only the trajectory of one aircraft is shown; however, the opponent's maneuver would look similar depending on initial conditions and performance.

There is an interesting similarity between the dynamics of SR and MR air combat engagements, even though position, speed regime, missile guidance, and tactics differ. Figures 12 and 13 show time histories of rate-of-turn, rate-of-climb or descent, and speed of one of four fighter aircraft in a sophisticated engagement against fighter-escorted intruders.

The level of turn rate is much lower than in SR combat. The maneuver is similar to a barrel roll with a moderate change of heading throughout a typical combat cycle. SEP contours depend on aircraft performance.

Figure 14 represents a simplified closed-loop maneuver typical for future MR combat, for which Eqs. (1) and (2) are applied as for SR combat.

Figure 15 shows the power margin which is left over for maneuvering. Contrary to SR combat (see Fig. 8), that maneuver power margin is only a small fraction of total propulsion power.

Most of the engine thrust is needed to compensate for the high supersonic drag. Figure 16 shows the utilization of that remaining power margin throughout the maneuver cycle. The power needed for turning is kept within the available budget. Any excess power which is not used for turning is used for either climb or acceleration; however, the total power demand does not exceed the available power by more than a factor of about 1.5. Roughly, acceleration is performed at the expense of altitude, and climb is performed at the expense of speed. Overall, and in comparison to SR combat, MR combat is less dynamic, and is characterized by very careful power management.

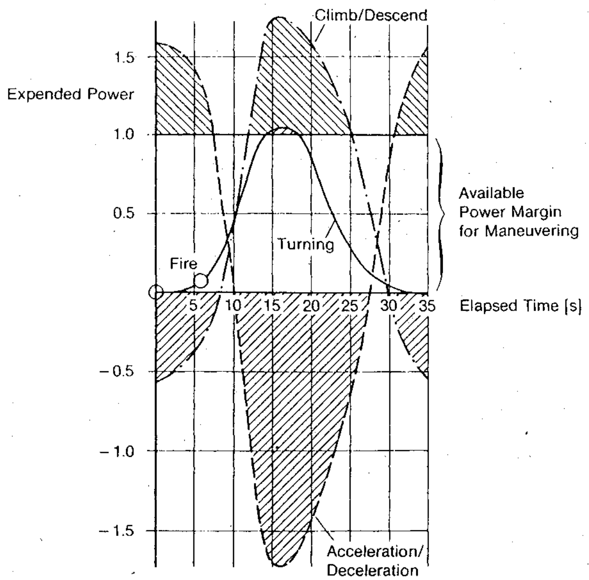

Fig. 16 Power management in a typical MR combat maneuver cycle.

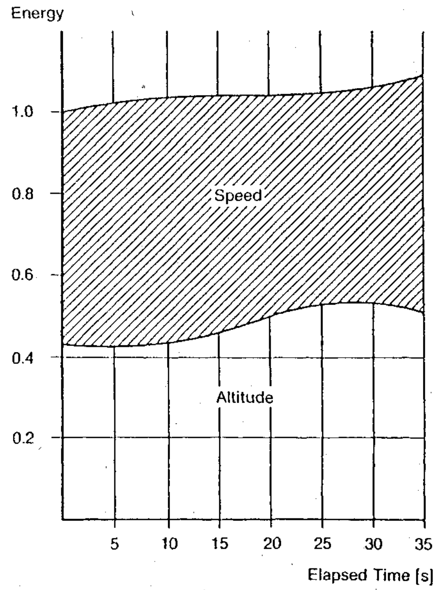

Fig. 17 Breakdown of energy status in a typical MR combat maneuver cycle.

There is no loss of energy (Fig. 17), and therefore no need for a recovery of energy. This is a result of the relatively small maneuver power margin and the high basic thrust demand for supersonic flight.

Any increase in T/W would significantly improve the maneuver capability and contribute to combat success, respectively. Figure 12 indicates specifically that it is important to be able to sustain a rate of turn at a load factor of about 4 or 5g. This requirement seems to be fairly independent of the speed level (see Fig. 12) and of the general aircraft performance level. The rationale for the need of a 4-5g turn in MR combat is related to the guided missile flight time and the gimbal limit of the fire-control radar.

Fighter Design Requirements

The analysis of maneuver characteristics in SR and MR combat may give an indication of future fighter aircraft design requirements for maximum combat capability.

SR combat is characterized by an extensive use of attained maneuvers; thus emphasis should be placed on high usable maximum lift. Low wing loading would be useful. Thrust-to-weight ratio should be high enough to recover the energy overspent during attained maneuvering.

MR combat is characterized by sustained moderate-g maneuvers at supersonic speed and high altitude; thus emphasis should be placed on low wave drag. Wing loading should be as low as necessary to get maximum speed at a sustained moderate-g maneuver for any given thrust-to-weight ratio.

An increase of steady-state maneuver performance for SR combat leads to an increase of maneuver dynamics at constant speed level, and for MR combat to an increase of speed level at a constant level of maneuver load factor.

Concluding Remarks

New short- and medium-range weapons must be expected to change air combat characteristics significantly. Short- and medium-range combat maneuvers are very dynamic in terms of a continuous interchange of speed, rate-of-turn, and rate-of-climb. Short-range combat is drifting to lower speed; it is characterized by extensive use of attained maneuvers and a fluctuation of total energy. Medium-range combat takes place at supersonic speed. It is characterized by very careful energy management and constant total energy. Consequently, design requirements for fighter aircraft will change. Advanced delta wing configurations lend themselves particularly well to a combination of good short- and medium-range combat capability.

References

[1] Herbst, W.B., "Future Fighter Technologies," *Journal of Aircraft*, Vol. 17, Aug. 1980, pp. 561-566.

[2] Frenzl, H.W., Polis, R., Pospischil, O., and Wimbersky, G., "Entwurf für den Luftkrieg" ("Design for Air Combat"), MBB Report MBB/FE1/TKR/STY/0064.