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Improved Missile Control Effectiveness Payoffs

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Simplified planar air-to-air engagements are examined to indicate the effects of various missile characteristics on the average time to intercept a target. For example, in a typical case the missile should be capable of 30 g maneuvers with an overall time constant no greater than 0.5 s. These parameters are related, in turn, to missile geometry and flight conditions. One significant finding is the actuator torque required, which must exceed the maximum hinge moment.

Nomenclature

a = missile acceleration (maneuverability)
a_0 = predicted maximum maneuverability
a^* = normalized maneuverability, $a_0/(V_M/T)$
l_B = body normal-force moment arm
l_c = control-force moment arm
R = initial range
R^* = normalized range, $R/(V_M T)$
T = time constant
t = time from beginning of control deflection
V_M = missile velocity
V_T = target velocity
V^* = velocity ratio, V_T/V_M
α = angle of attack
δ = control deflection angle
θ = missile flight-path angle
θ_i = initial missile flight-path angle

Introduction

GREATER maneuverability and faster response will generally improve a missile's ability to intercept a target. However, enhanced missile responsiveness may require larger aerodynamic control surfaces, more thrust, heavier structure, greater actuator weight and power, and increased cost. Therefore, some measure is needed of the improvement in performance that can be gained by increases in missile maneuverability and decreases in time constant.

This report provides a quantitative measure of the effects of a missile's maneuverability and time constant on its ability to intercept an aircraft target. Performance comparisons can then indicate desirable levels of missile maneuverability and time constant.

In addition, however, it is necessary to have some means of relating the desired maneuverability levels to the parameters associated with the missile and of relating these parameters to missile geometry and flight conditions. All of these required capabilities are addressed so that changes in missile design can be reflected in corresponding ability to intercept air targets. Additional details are available elsewhere.[1]

Effects of Maneuverability and Time Constant on Intercept Trajectories

Intercept Trajectories

An assumed engagement is illustrated in Fig. 1. In missile-centered coordinates, the x axis is fixed by the direction of the target's velocity V_T. The missile is traveling at velocity V_M at an angle θ with respect to the x axis. Gravitational forces are ignored.

The guidance system assumes that the target will continue to travel at constant velocity and calculates the predicted intercept point, assuming that the missile also travels at its constant speed in the desired direction θ_i.

The guidance system immediately tells the missile to maneuver toward the predicted intercept point. The missile then proceeds to turn in the desired direction at an acceleration

$$a = a_0(1 - e^{-t/T}) \tag{1}$$

At the beginning of each engagement, the following parameters must be specified: V^*, R^*, a^*.

The kinematic equations of motion then can be integrated numerically until the distance to the target R is a minimum. If this distance is less than a prescribed allowable miss distance (normalized by $V_M T$), the engagement is terminated. If the minimum distance is too large, then the missile has missed its target; however, in the calculated trajectory, the missile circles around and reengages the target, eventually hitting it (within the specified miss distance).

Average Time to Intercept

The effects of maneuverability can be seen in Fig. 2. A missile with 30 g maneuverability hits this target from all initial directions.

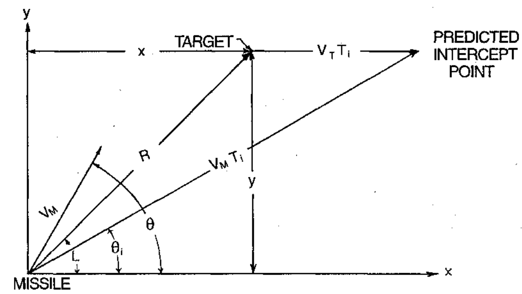

Fig. 1 Intercept geometry.

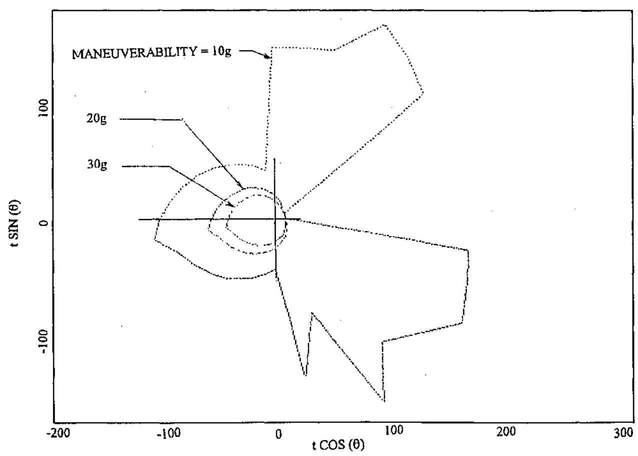

Fig. 2 Polar plots of time to intercept as a function of initial missile flight direction θ for maneuverability = 10, 20, 30 g; time constant = 3 s; range = 32,000 ft; V_M = 4000 ft/s; and V_T = 2000 ft/s.

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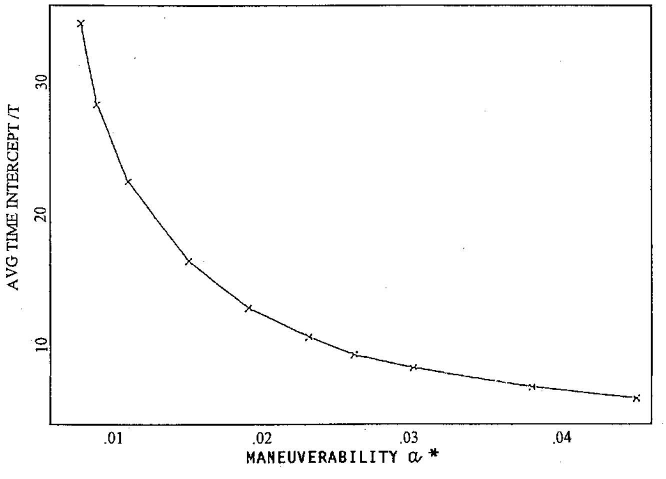

Fig. 3 Normalized average time to intercept as a function of normalized maneuverability: $R^* = 2.67$ and $V^* = 2$.

A missile with 20 g maneuverability takes a little longer. At 10 g, the missile fails in about half of its initial headings.

The average time to intercept over all initial missile and target headings makes a convenient measure of the effects of missile maneuverability and time constant. Figures 3–5 show the effects of maneuverability, velocity, ratio, and range on intercept time. The long average intercept times associated with poor maneuverability result from the time required to reengage the target after initial missiles.

The effect of velocity ratio is shown in Fig. 4. There is little advantage in missile speeds exceeding target speed by more than a factor of 2. However, when the target speed gets to 0.75 missile speed, even a highly maneuverable missile can take a long time to catch a target.

As shown in Fig. 5, increasing the range ratio decreases the intercept time and decreasing the ratio increases the intercept time, because the missile missed the target more often when the initial range was smaller.

Effect of Target Maneuvers

A target maneuver is represented by an amplitude and a frequency. At prescribed time intervals the target suddenly changes direction

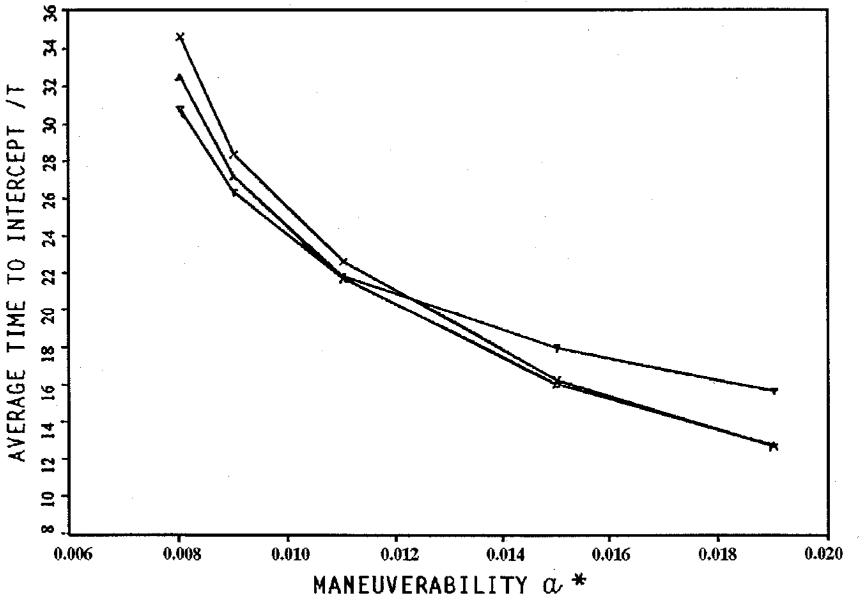

Fig. 4 Effect of velocity ratio on average time to intercept: △, $V^* = 0.25$; ×, $V^* = 0.50$; and ▽, $V^* = 0.75$.

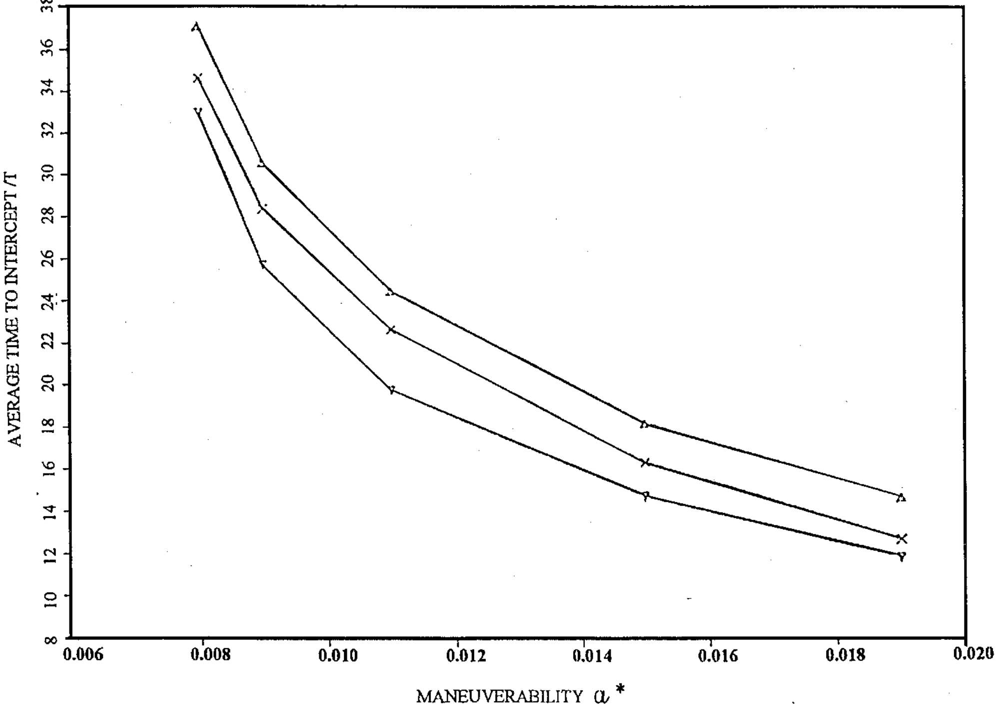

Fig. 5 Effect of normalized range on average time to intercept: △, $R^* = 0.667$; ×, $R^* = 1.667$; and ▽, $R^* = 2.667$.

by a specified angle, first one way, then the other. Polar plots of time to intercept a maneuvering and a nonmaneuvering target are superposed in Fig. 6. If the target happens to change its path shortly prior to intercept, then the missile will miss and be forced to reengage; resulting in the long time spikes evident in the figure. Usually, a more responsive, more highly maneuverable missile will follow the target motion better than a sluggish one. In some cases, however, the less responsive missile will partially ignore target motions and will be less affected by its maneuvers.

Effects of Missile Characteristics on Maneuverability and Time Constant

Missile Dynamics

Effects of missile dynamics can be determined from the three-degree-of-freedom equations of motion coupled with the equations of motion of the control surface. The process is illustrated elsewhere.[1]

To find the missile time constant, the equations for angle of attack and control deflection are integrated numerically to give $\alpha(t)$ and $\delta(t)$. Then, $\alpha(t)$ is compared with a specified maximum angle of attack α_M. The time constant is the time at which $\alpha/\alpha_M = 1 - 1/e = 0.632$. The controls trim the vehicle at an attitude that depends on a maximum available control deflection and the maximum allowable angle of attack.

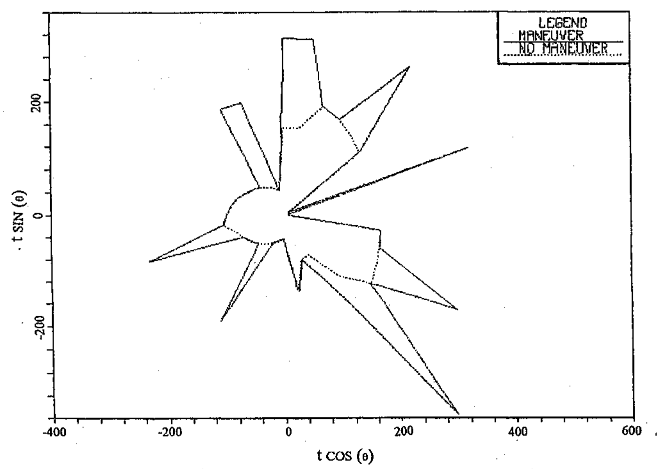

Fig. 6 Effect of target maneuverability on time to intercept.

Initially, all angles can be set to zero. However, it is more appropriate to start at a maximum negative trim angle of attack and corresponding control settings. Then, the time required to push the missile to the desired positive angle of attack should be measured.

Maneuverability

The determination of missile maneuverability and time constant, using the computer program COEF requires specification of the missile parameters occurring in the equations of missile motion.

The maneuverability may be increased by making the missile lighter or increasing the maximum allowable angle of attack, or by increasing the aerodynamic forces.

Also, the normal acceleration may be increased by increasing the ratio l_B/l_c and hence the force on the control surface required to trim the missile. Eventually, the resulting increase in control deflection will exceed the limits on the control or the capacity of the actuator.

Time Constant

The time constant can be reduced by increasing the control effectiveness, increasing actuator torque, or decreasing the hinge moment. A plot of time constant as a function of the ratio of actuator torque to hinge moment is shown in Fig. 7. Once the actuator torque exceeds the hinge moment by a small amount, the control surface moves rapidly, and the time constant is then determined primarily by the ability of the aerodynamic forces to overcome the inertia of the missile. The calculated time constant accounts for only the response of the missile airframe to control-generated forces. The control-system time constant and the effects of other time delays must be evaluated separately.

Effects of Thrust Controls

If a thrust control is used, it is assumed to operate to help turn the missile to a high angle of attack where the aerodynamic forces maintain trim and maneuverability while the thrust control is turned off. In this application the thrust reduces the time constant but does not influence the maneuverability. The effect of thrust augmentation added to the aerodynamic forces on the canard-controlled missile is shown in Fig. 8. The rate of change of thrust contributes a form of damping, which can adversely affect the time constant.

Relation to Missile Geometry

To realize the desired missile aerodynamic characteristics, it is necessary to relate the aerodynamics to missile geometry and flight conditions. Any missile design or analysis technique may be used.

The same program can be used to determine the modifications of airframe shape that will result in desired values of maneuverability

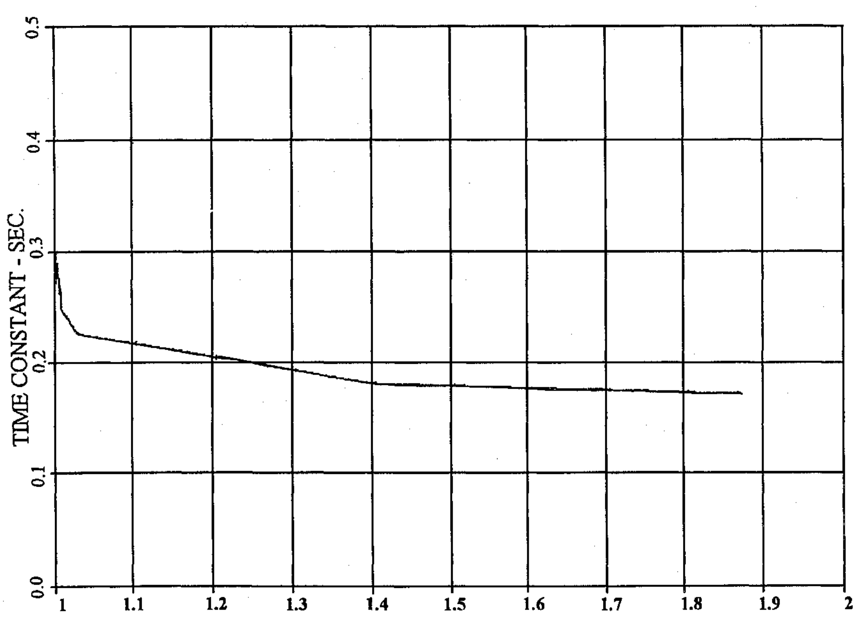

Fig. 7 Effect of actuator torque ratio on time constant.

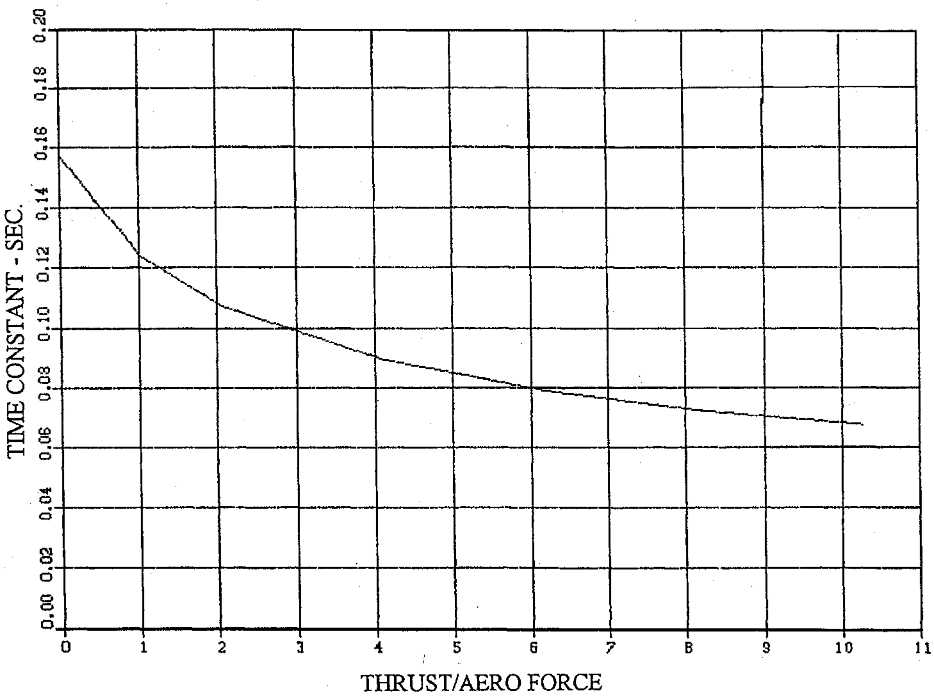

Fig. 8 Effect of thrust augmentation on time constant.

and time constant. In a typical example, increasing the body normal-force coefficient slope by 10% would result in a 10% increase in maneuverability. The aerodynamic characteristics calculated for a missile with an increase in wing span indicate an increase in normal-force coefficient accompanied by a slight rearward shift of center of pressure.

Conclusions

With the postulated idealized guidance system, this study indicates that, in a typical engagement, for reliable interception, maneuverability should be at least 30 *g* and time constant should be less than 0.5 s. These characteristics are obtainable with reasonable airframe components.

One of the critical parameters is the ratio of actuator torque to control hinge moment. If the missile encounters a flight condition at which the actuator torque is inadequate, then it is likely to tumble out of control. Although excess torque resulted in only small reductions in time constant for the cases considered here, it is absolutely critical to have enough torque for any flight condition. This result can be achieved by making the actuator sufficiently powerful, at corresponding cost in weight and volume as well as energy. Reducing the maximum required hinge moment while retaining high maneuverability is a more attractive solution, addressable by improvements in control surface design.

Reference

[1] Schindel, L. H., and Lam, L., "Improved Missile Control Effectiveness Payoffs," *Proceedings of the AIAA 13th Applied Aerodynamics Conference* (San Diego, CA), AIAA, Washington, DC, 1995, pp. 1101–1110.

R. M. Cummings
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