Computational Method for Determining the No-Escape Envelope of a Short-Range Missile

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Abstract

A METHOD is described for solving the missile-avoidance problem for a realistically modeled fire-and-forget missile. The method combines analysis and detailed simulation to derive data for missile avoidance and attack over the complete operational envelope of the missile.

Contents

Introduction

Problems arise when systems are too complex to be modeled fully. In those cases, in an attempt to obtain an optimal solution to a problem, the system equations are often simplified to such an extent that the validity of the solution may be affected. Here we are interested in solving the missile-avoidance problem for a realistically modeled fire-and-forget missile by obtaining its no-escape envelope, a concept first introduced by Shinar and Gazit.[1] Some attempts at maximizing the missile miss distance optimally have required that the missile and the target aircraft fly at constant speed.[2] This simplification allows infinite missile range, which would lead to incorrect conclusions when obtaining the no-escape missile envelope. In the literature, only a few sample solutions are given, which are insufficient to gain insight into the problem over the whole domain of initial conditions. In Ref. 3, a new method that eliminates these difficulties was used to solve the missile-avoidance problem. The basic concept was 1) to identify alternative control laws or strategies that may be reached optimally, through the solution of simplified versions of the problem or heuristically, based on evasion strategies used by combat pilots; 2) to test the alternative controls over a discretized initial condition space using complete models of the missile and target aircraft; and 3) to segment the initial condition space based on the results of the preceding simulation into regions within which different control strategies gave the best results. In this way the optimization problem is reduced to discrete optimization over a finite set of control strategies without compromising the complexity of the problem. This method may be applied to other engineering problems as well, as demonstrated in a more rudimentary form earlier.[4,5] A synopsis of Ref. 3 is presented here.

Method

This is an engineering method. As such its application takes experience, and no handbook solution or set of rules can be given. However, the following steps must be accomplished.

Select Realistic Simulation Models

Find the best possible simulations of the system under consideration. In this example, a complete six-degree-of-freedom missile model, including motor, control laws, and realistic missile-failure modes, was used. The target model was an F-15 fighter aircraft with proper thrust and drag characteristics and *g* limits.

Select Candidate Control Laws

Define candidate control laws using any reasonable technique. To do this, we 1) interviewed pilots to understand their techniques for missile avoidance and 2) obtained results from optimal control theory based on the solution of a simplified problem.[2]

Discretize Initial Condition Space

Select the initial condition space over which the problem must be solved, and discretize the space to obtain a sufficient set of trials. The discrete step sizes may have to be changed during the problem solution. They must be sufficiently small to determine regions where different control laws are effective without being so small that the computational load becomes excessive.

Optimize Control Law Parameters for Each Initial Condition

For each suggested control law and each initial condition, simulate the system to optimize the control parameters. For the missile-avoidance problem, four separate control laws were identified (see Fig. 1). These four control laws were defined as turning toward the missile (turn head-on) or turning away from the missile (turn tail) followed by either a single sharp bank maneuver (break turn) at the appropriate time, or a series of bank reversals (weave maneuver). The parameters optimized in each case included the ranges to the missile at

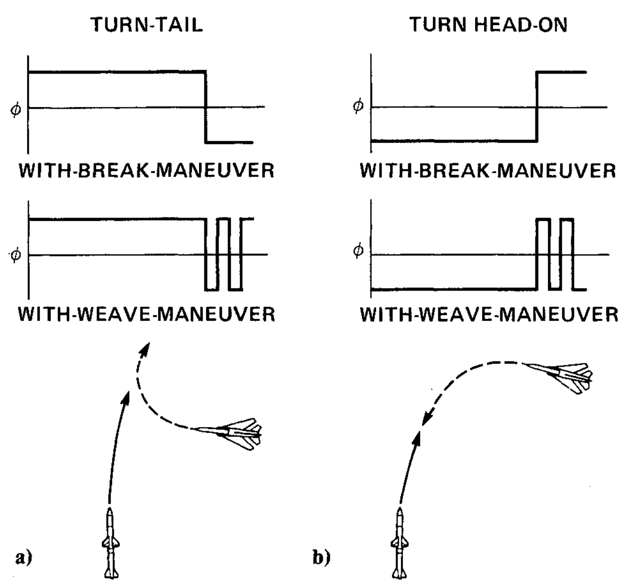

Fig. 1 Avoidance maneuvers.

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which the transient maneuver should be initiated, and in the case of the weave maneuver, also the rates at which the weaves should occur. This is a time-consuming task for the computer. When the requirement is to achieve a sufficiency condition (such as to "exceed the minimum lethal separation distance") rather than to achieve an optimum (such as to "maximize the minimum separation distance"), start with the simplest strategy to see whether it does the job. If it does, more complex strategies do not need to be evaluated for that particular initial condition. For missile avoidance, the "missile hit or miss" was not very sensitive to the distance at which the transient maneuver should be started, and a few iterations sufficed to find a parameter that guaranteed successful missile avoidance or to prove that the control law was ineffective to avoid the missile.

Develop the Overall Strategy

Plot the data in various ways to gain insight into the problem. These plots may also give information about which regions of the initial condition space need to be explored further using a more finely quantized grid or about when data storage may be reduced or simplified for the operational system. For the missile-avoidance problem, this means plotting the target-centered, no-escape launch envelopes. These envelopes provide information about launch conditions that result in almost certain destruction of the target aircraft.

Use the data to make decisions about the choice of control law—first in a simulation, then in the fully implemented system. For the missile-avoidance problem, the data were used in two ways. First, they were used by the attack aircraft, assuming the opponent was aware of the attacker, to determine whether the missile should be launched. (If the opponent is not aware of the attacker, a much larger kinematic launch envelope can be used.) Second, they were used by the target aircraft for missile avoidance, to determine the optimal avoidance maneuver.

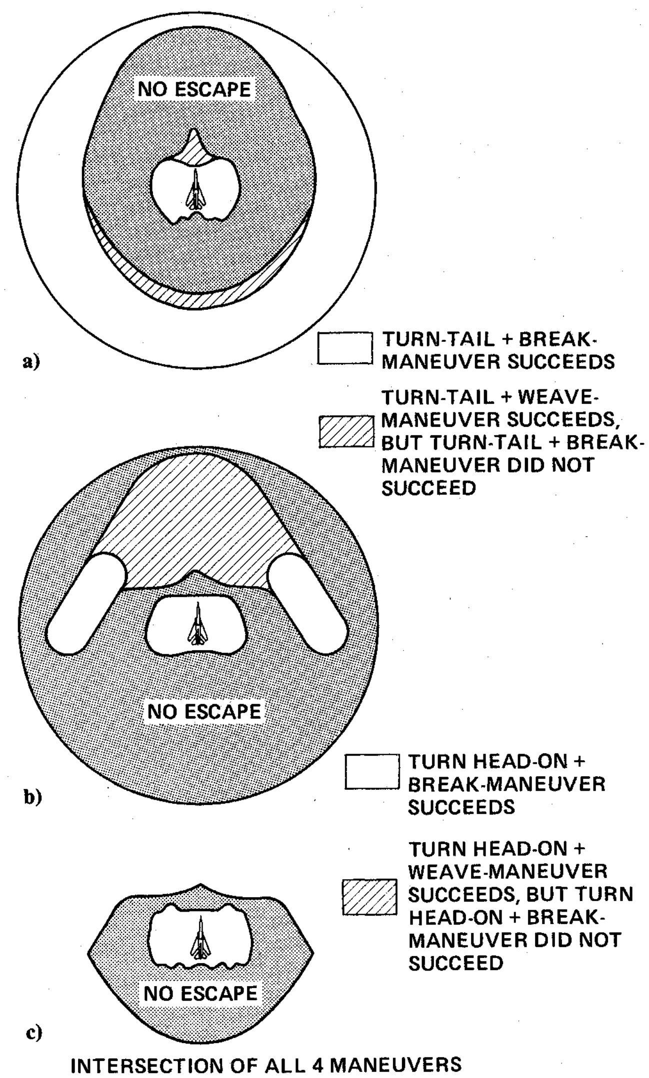

Fig. 2 No-escape zones.

Results

Two F-15 fighters were simulated flying at a constant altitude of 20,000 ft. Both were equipped with all-aspect, short-range missiles of the fire-and-forget type. The missile and its control laws were modeled in detail and had seven different criteria for missile failures: 1) Maximum time of flight exceeded, 2) ground impact, 3) below minimum Mach number or minimum closing rate after the missile came up to speed, 4) seeker track failure, 5) gimbal look angle exceeded, 6) below minimum time of flight to arm missile, and 7) excessive miss distance.

The simulation could be flown manned vs automatic and automatic vs automatic. Figure 2 shows examples of target-centered no-escape zones for boresight missile launches in which target and missile-firing aircraft are initially at relatively high speeds (Mach 0.95). Figure 2a shows the no-escape zone when only the turn-tail maneuvers are used. Figure 2b shows the resulting no-evade zone when the initial response to the missile attack is to turn the aircraft head-on toward the missile. The overall no-escape zone for which no known aircraft maneuver was successful is shown in Fig. 2c. When the target is at lower speed, the maneuvers used for Fig. 2b are less effective.

Additional data were obtained from 120 simulated engagements of manned vs unmanned aircraft. When missiles from either aircraft were fired within the no-escape region, all were hits regardless of evasive actions. Attempted evasion using the no-escape data was successful only when the opponent fired while the evader was not within the no-escape missile envelope.

Conclusions

We have drawn the following conclusions about our new computational method:

1) The method gives insight and approximate answers to difficult missile attack-and-avoidance problems.

2) No-escape data can be improved stepwise as additional guidance laws are considered.

3) Success regions for different guidance laws are well defined.

4) We may take advantage of missile limitations not considered in a simplified optimization approach.

5) Storage requirements for table lookup were not excessive, even though different initial speeds for combatants were considered.

6) No-escape data can be successfully used for both missile attack and missile avoidance.

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