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TACTICAL MISSILE CONCEPTUAL DESIGN.(U)

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

TACTICAL MISSILE CONCEPTUAL DESIGN

by

Danny Ray Redmon

September 1980

Thesis Advisor: G.H. Lindsey

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This thesis presents the theory necessary for the conceptual design of a tactical missile. The design process begins with the well known linear aerodynamic theory for initial sizing and later includes non-linear effects to determine the final design of the missile. Where theory does not apply, empirical methods are presented which are known to give accurate results. An air-to-air missile is designed for a specific threat as an example which immediately follows the development of the theory for each section. Several small digital

computer programs are presented and used for analysis of specific areas of the design. One large program (AERO1) is used for determining the aerodynamic coefficients of the final design.

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Tactical Missile Conceptual Design

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

This thesis presents the theory necessary for the conceptual design of a tactical missile. The design process begins with the well known linear aerodynamic theory for initial sizing and later includes nonlinear effects to determine the final design of the missile. Where theory does not apply, empirical methods are presented which are known to give accurate results. An air-to-air missile is designed for a specific threat as an example which immediately follows the development of the theory for each section. Several small digital computer programs are presented and used for analysis of specific areas of the design. One large program (AERO1) is used for determining the aerodynamic coefficients of the final design.

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I. INTRODUCTION

This study was made to present a method for the conceptual design of tactical missiles. The starting point for the design was a recently completed report by General Dynamics, Convair Division entitled Rapid Approach to Missile Synthesis (RAMS). A procedure was then developed more akin to aircraft design and which bears little resemblance to RAMS and which uses basic equations to size components rather than nomograms and table look-up. The procedure starts with a threat description and proceeds with the formulation of performance objectives and a conceptual design of a tactical missile to counter the threat. The design is not unique, but as will be shown, is a compromise of parameters to give one possible solution to the design problem; therefore, the point design arrived at is not necessarily the optimum design for the presented threat. An attempt is made to find the optimum performance within specific areas of the design process.

Throughout this study the theory involved is explained and specific examples are worked. A complete design example is worked out in detail. It is an air-to-air missile designed to counter the new Soviet RAM-K fighter aircraft. This example is worked in each section immediately following the development of the theory for that specific area.

II. PROBLEM DEFINITION

A. THREAT ANALYSIS

1. Operational Requirements

The design of a new missile is usually in response to an operational requirement which arises as the result of one of the following: (1) A new technology provides the means to design a more effective missile to meet a current threat. An example of this might be an advance in material science, which allows higher inlet turbine temperatures for a turbojet engine; therefore, allowing higher missile flight speeds. (2) Intelligence indicates a new threat for which existing missiles are not effective. (3) Operational reports indicate a current missile is inadequate against a current threat.

Regardless of how the operational requirement is derived, a statement of the threat is required before the design process can proceed. Experience has proven that one missile cannot be designed to meet all types of threats without seriously compromising performance or effectiveness. This can be illustrated with the design of the warhead. A contact fuze, shaped charge warhead designed to penetrate and kill hard targets such as tanks, would not be effective against a highly maneuverable aircraft for which the expected miss distance is several feet. For this reason the design of a missile must start with a detailed analysis of the threat. The more detailed this analysis is, the more effective the final design can be.

2. <u>Design Example (Operational Requirement)</u>

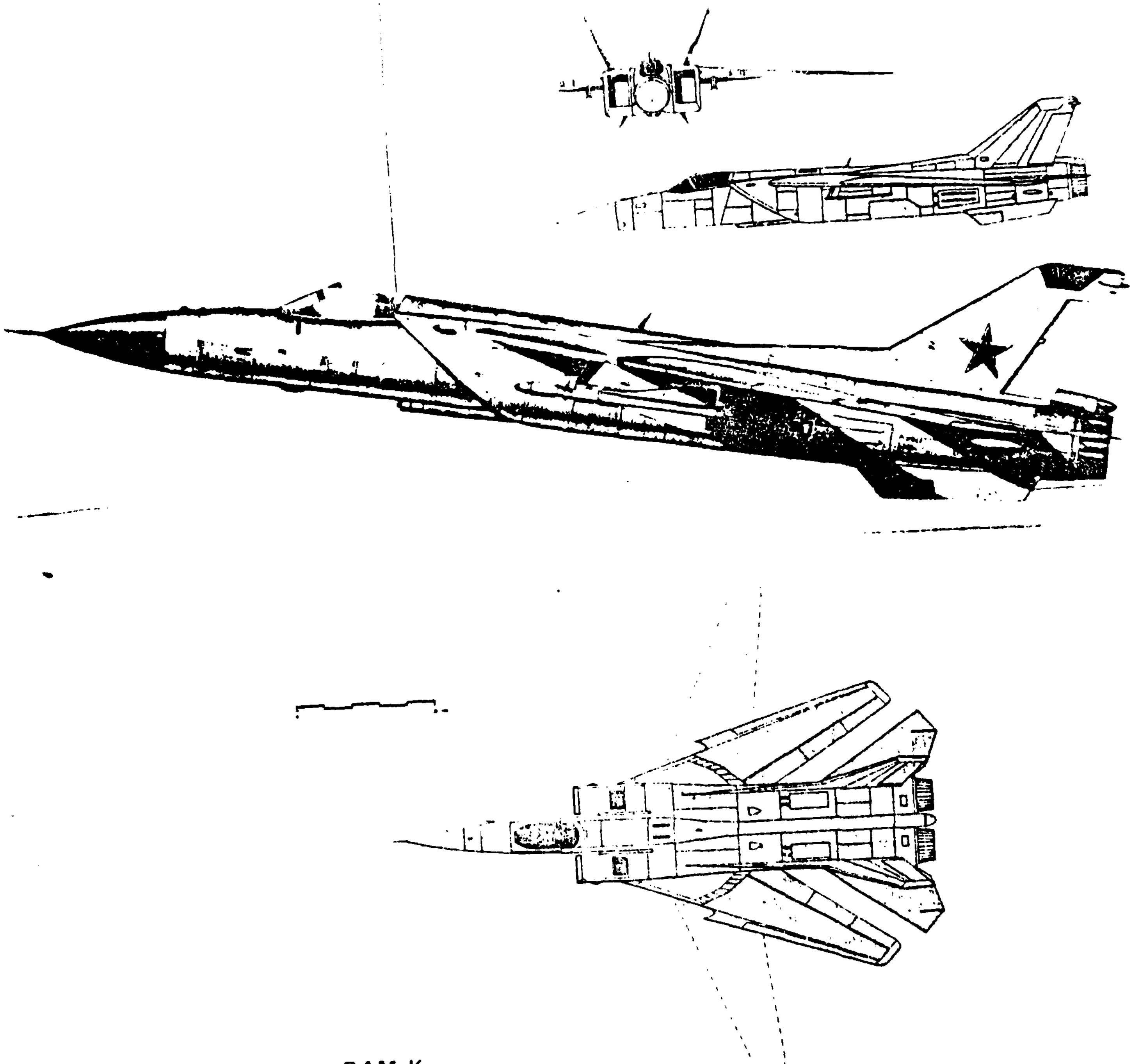
A design example will be used as a continuous thread throughout this thesis to demonstrate applications of the theory. An air-to-air missile will be designed to counter the new class of Soviet fighter, which is in the advanced development stage at the Ramenskoye Experimentation Center. The fighter, as described in Aviation Week [1,2] has been designated the RAM-K. The RAM-K is a twin engine fighter with variable geometry inlets and swing wings. The aircraft bears a resemblance to both the F-14 and F-15. It is expected to be the recipient of a new look down, shoot down radar and the 40 km range AA-X-9 missile. The following unclassified dimensions and performance data are available on the RAM-K:

Wing span	40 ft
Overall length	64 ft
Gross weight	60,000 lbs
Maximum speed	M=2.5
Service ceiling	60,000 ft

Figure (2-1) is a drawing of the RAM-K.

3. <u>Scenario</u>

The scenario within which the missile is expected to operate should also be described. If the normal mode of operation of the threat is not known, an attempt should be made to define the most demanding scenario that can be expected. For a defensive weapon the most challenging incoming threat will normally be a head-on encounter. The threat profile may vary from a high level attack with a terminal dive to a low level attack with a



RAM-K

Figure (2-1). RAM-K Fighter.

terminal pop-up maneuver. In the case of the AS-6 (Kingfish) two modes of attack can be expected. In such a case both profiles must be evaluated to determine the most demanding in terms of missile performance objectives. For an offensive system, such as an air-to-air missile designed to intercept and destroy an enemy fighter before it launches its weapons, the scenarios analyzed should include all possible encounter geometries.

4. Design Example (Scenario)

The scenario for the above threat would likely be an intercept situation in defense of the fleet high value unit. The scenario is taken to be a head-on encounter with the missile and the target at the same altitude. Since the combat specifications of an aircraft are normally given at 10,000 ft., this is taken as the scenario altitude.

B. HISTORICAL SURVEY

Missile design is an iterative process, and the first time through the design loop many assumptions have to be made concerning component sizes and weights. One method of approach at the early stage is to employ historical data of existing missile sizes and weights; since justifications for these parameters were made duirng their design processes. An example of the use of historical data in determining the initial missile length can be made with the length to diameter ratio. The length to diameter ratios of existing missiles of the same class as that being designed are collected, and an average is computed. The diameter of the design is fixed by one of three driving factors (propulsion, warhead, or guidance). From the average length to diameter ratio the initial missile length is then estimated. From this historical data, initial choices based on the experience of others can be made for many of the missile parameters. These parameters define a baseline missile, which is the initial configuration from which design iterations and refinements can be made.

Since missiles are designed for specific missions, specific parameters such as length and diameter are of little value in comparing missiles. Dimensionless ratios such as length to diameter, L/D, ratio and aspect ratio, AR, are more meaningful when relating missiles. Some parameters which are useful in defining the baseline missile are listed below:

L/D = Length to diameter ratio

L_n/D = Nose length to diameter ratio

AR_w = Aspect ratio of the wing

AR_t = Aspect ratio of the tail

W/S = Weight to lifting surface area ratio

$V_t = S_t l_t/(S_{ref} d_{ref})$ Tail volume coefficient

W_G/W_{wh} = Gross weight to warhead weight ratio

The tail volume coefficient, V_t, is a dimensionless parameter used to initially size the tail. For a tail control missile, it is a measure of the relative control effectiveness when comparing missiles. For a wing control missile it is a relative measure of stability.

TABLE 2-I

HISTORICAL DATA

Missile	L/D	L_n/D	Ar_w	$AR_{t/c}$	W/S	$S_{t/c}/S_w$	$V_{t/c}$	W_g/W_{wh}
ASALM	8.00							
Phoenix	10.00	2.32	.60	1.53	134.20	.40	5.76	
Sidewinder[c]	23.75	2.00	.97	4.00	50.60	.20c	38.88	8.22
Sparrow	17.14	2.40	2.82	2.59	121.95	.60	28.80	5.72
Magic	18.82							7.17
R530	12.58		1.48	2.15	60.31	.32		7.23
Sky Flash	17.29	2.00	.97	4.00	50.60	.20	38.88	5.68
Shafrir[c]	17.00		1.36	3.48c	70.45	.21c		8.44
Aspide	18.43	2.42	2.84	2.77	110.90	.58	30.43	6.30
<u>Average</u>	15.89	2.23	1.61	2.61 3.74c	88.09	.42 .20c	28.55	6.97

A complete historical survey should not be limited to the parameters listed here. Any dimensionless parameter which will add information about the proposed design should be included for completeness.

Table 2-I is an example of a collection of such parameters for existing air-to-air missiles [1,3]. In this table the subscript, c, is used to indicate a canard control surface.

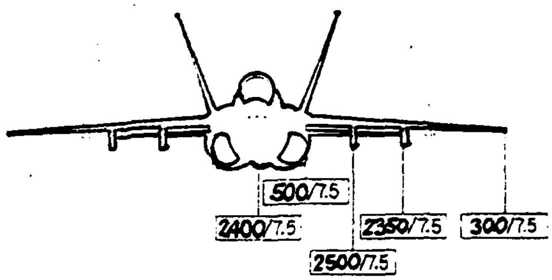
C. LAUNCH PLATFORMS AND PHYSICAL CONSTRAINTS

The problem definition must also include a description of the intended launch platform for the missile. The aircraft or shipboard launcher from which the missile will be launched will fix many design features of the missile. For instance the most important consideration in the problem definition phase is any physical constraints imposed by the launcher. Since it is not normally feasible, economically to design a launcher to fit the missile, most new missiles must fit existing launchers. In the case of shipboard launchers there will be a maximum length and diameter and a maximum launch weight which can be accomodated.

For the case of an air launched missile, there will be a maximum weight, and the dimensions may also be limited due to the performance requirements of the aircraft.

For the air-to-air missile design example of this study, the launch platforms will be the F-16 and F-18A. Figure (2-2), which is from Interavia [4,5] shows the pylon weight limitations for these aircraft. From these figures it can be seen that the maximum launch weight for this design is limited to 2500 pounds by the pylon limitations of the F-18A.

Load Carrying Capability of F-18A



Load Carrying Capability of F-16

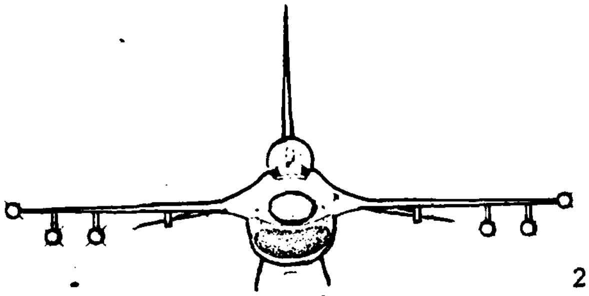


Figure (2-2). Weight Limitations.

D. MISSION PROFILES AND PERFORMANCE OBJECTIVES

The mission profile of a missile consists of dividing the flight into fundamental segments which consist of a single function, such as boost to cruise speed and altitude, cruise to the target, and terminal homing phases. The mission profile will vary from missile to missile. For a cruise missile it may consist of a series of pop-up maneuvers and low level cruises. For a short range missile, the profile may be entirely terminal homing. The Mach number and altitude are specified at the beginning and end of each mission segment, as well as the range covered by each segment. The range covered by a segment can be considered in one of two ways. If the segment is short, such as the terminal phase, the distance along the intended flight path is considered. For longer range missiles, the distance over the ground is of importance. The mission profile must be defined during the problem definition phase in order to specify missile performance objectives.

The mission profile of a missile normally consists of a boost, cruise (mid-course) and terminal phase. The boost phase accelerates the missile to its flight speed. This acceleration may be large for a surface-to-air missile which must be accelerated from rest to a high supersonic speed or it may be small for an air launched missile which has the speed advantage of the aircraft from which it is launched.

The cruise segment, or mid-course phase, primarily is used to deliver the missile to a point in space where the seeker can acquire the target. The range and speed of the cruise segment is then a function of the required stand-off distance for the target.

The terminal phase is somewhat more difficult to analyze. If the target maintains constant heading and velocity the flight path of the missile may be modeled by circular arc segments. This method will give approximate values of range. If the target maneuvers, the missile must follow and the range and speed requirements become more complicated.

In determining the range and speed requirements, all expected encounter geometries should be analyzed. The most demanding encounter will then fix the performance objectives. The most demanding speed requirement, in terms of maintaining a minimum stand-off distance, will normally be a head-on encounter. Although the required missile speed and range are determined in this section, the missile velocity may be varied later in the design process due to guidance considerations.

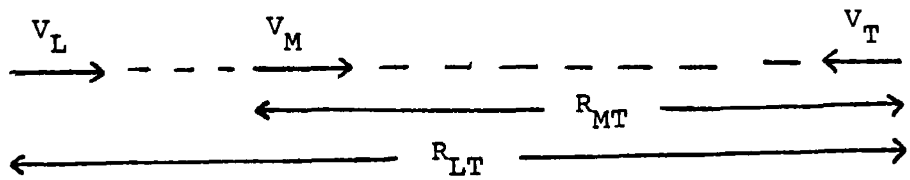
1. <u>Design Example (Mission Profile)</u>

From the threat defined above, the ideal situation would be to obtain a fire control solution and launch such that the minimum separation distance between the launch aircraft and the target is 40 km. This can be accomplished in one of two ways. The launch aircraft can fire a semi-active homing missile at such a range and speed that intercept occurs before the minimum range is reached, or an active homing missile can be fired, and once missile lock-on is achieved, the launch aircraft can maneuver to maintain the minimum separation distance.

The active radar homing missile would decrease the launch range and the range required of the missile, which will lessen the constaints on the launch aircraft. The terminal portion of the engagement is a function of the guidance law and will be determined in Chapter 3.

Two cases are investigated to determine the effect on the range requirement of the missile when a minimum separation distance from the target to the missile of 40 km is maintained. The first case is a semi-active homing missile, for which the launch aircraft must maintain a closing course until intercept. The second case is an active homing missile which has a lock-on range of 10 km. The launch aircraft may then maneuver to maintain a separation distance.

a. Case 1: Semi-active homing missile



R_0 = Range at which the missile is launched

M_L = 1.5 = Launch Mach number

M_M = 2.5 = Missile Cruise Mach number

a = Speed of sound

$V_L = M_L a = 1.5a$ = Launch speed

$V_T = M_T a = 2.5a$ = Target speed

$V_M = M_M a = 2.5a$ = Missile speed

The instantaneous range from the missile to the target is given by, R_{MT}

$$R_{MT} = R_0 = (V_M + V_T)t \tag{1}$$

The instantaneous range from launch aircraft to the target is given by, R_{LT}

$$R_{LT} = R_0 - (V_L + V_T)t \tag{2}$$

If the target does not maneuver, intercept will occur at t_f, when $R_{MT} = 0$

$$0 = R_0 - (V_M + V_T)t_f$$

$$t_f = \frac{R_0}{(V_M+V_T)} = \frac{R_0}{5a}$$

If the launch aircraft is at the minimum separation distance, $R_{LT} = 40$ km, when intercept occurs.

$$40 \text{ km} = R_0 - (V_L + V_T)t_f$$

substituting for V_L, V_T and t_f

$$40 \text{ km} = R_0 - (1.5 + 2.5)a(\frac{R_0}{5a})$$

Solving for R_0

$$R_0 = 200 \text{ km} = \text{Launch range}$$

The range required of the missile is then, R_M.

$$R_M = V_M t_f = 100 \text{ km} = 53.96 \text{ nmiles}$$

If the missile speed is increased to $M_M = 3.0$, then $R_0 = 148.15$ k and,

$$R_M = 80.81 \text{ km} = 43.61 \text{ nmiles.}$$

b. Case 2: Active Homing Missile

The lock-on range is a function of the seeker in the missile and will be covered later in this thesis. If it is assumed that the launch aircraft must maintain its course until lock-on occurs at a range of R_{LO}, the problem can still be solved. The geometry is the same as in Case 1. Instead of following a constant course until intercept, the launch aircraft must now only maintain a closing course until $R_{MT} = R_{LO}$. Then from equation (1)

$$R_{MT} = R_{LO} = R_0 - (V_M + V_T)t_{f1}$$

Solving for t_{f1}

$$t_{f1} = \frac{R_0 - R_{LO}}{(V_M + V_T)}$$

If at the time of target lock-on, t_{f1}, the target and launch aircraft are at the minimum separation distance, $R_{LT} = R_{min}$, from equation (2),

$$R_{LT} = R_{min} = R_0 - (V_L + V_T)t_{f1}$$

Inserting for t_{f1},

$$R_{min} = R_0 - (V_L+V_T)(R_0-R_{LO})/(V_M+V_T)$$

Solving for R_0,

$$R_0 = \frac{R_{min}}{\left[1 - \left(\frac{V_L+V_T}{V_M+V_T}\right)\right]} - \frac{\left(\frac{V_L+V_T}{V_M+V_T}\right) R_{LO}}{\left[1 - \left(\frac{V_L+V_T}{V_M+V_T}\right)\right]} \qquad (3)$$

For the same geometry and relative speeds of the first case, with $M_M = 3.0$,

$$t_{f1} = \frac{R_0-R_{LO}}{5.5a}$$

A reasonable value of lock-on range is 10 km. This will be shown later in the guidance section of the study. The time to lock-on then becomes,

$$t_{f1} = \frac{R_0-10}{5.5a}$$

From equation (3), R_0 then becomes, $R_0 = 118.52$ km . The missile range to lock-on is then, R_{M1},

$$R_{M1} = V_M t_{f1} = 59.19 \text{ km} \quad .$$

If the target does not maneuver the time from lock-on to intercept becomes, t_{f2}.

$$t_{f2} = \frac{R_{LO}}{(V_M+V_T)}$$

and the missile range from lock-on to intercept becomes,

$$R_{M2} = V_M t_{f2} = 5.45 \text{ km}$$

The total missile range is then the sum of the two,

$$R_M = R_{M1} + R_{M2} = 64.64 \text{ km} = 34.88 \text{ nmiles} .$$

As can be seen from the above analysis, both the detection range of the target and the required missile range are decreased significantly when an active homing missile is used. On the other hand, it must also be remembered that the complexity and cost of the missile will be increased as a result of choosing an active radar seeker. For the design example in this study, an active radar seeker is chosen; therefore, the maximum range requirement will be 35 nmiles at a speed of $M_M = 3.0$, however, this missile velocity is tentative until a guidance analysis is complete.

From the preceding analysis the mission profile is determined. It must be kept in mind that the mission profile may be changed during the design process to meet other design objectives. The following profile assumes both the target and launch aircraft at the same altitude.

	SEGMENT	M_{begin}	h_{begin}	M_{end}	h_{end}	RANGE
(1)	Boost	1.5	10,000 ft	3.0	10,000 ft	
(2)	Cruise	3.0	10,000 ft	3.0	10,000 ft	29.6 nmiles
(3)	Terminal	3.0	10,000 ft	3.0	10,000 ft	5.4 nmiles

III. GUIDANCE LAW SELECTION

Although the specifics of the guidance system is beyond the scope of conceptual design, the selection of a guidance law is necessary for initial calculations. The warhead design depends on the expected miss distance between the missile and the target and the lifting surface area depends on the maneuvering requirements of the missile. Both the miss distance and maximum acceleration required are functions of the missile guidance law.

The guidance law for a missile is the analytical formulation used by the guidance system to convert sensed target information into missile steering commands. Three general guidance laws are used. Most others can be forced to fit into one of these categories. These are:

1) Pursuit Guidance

2) Line-of-Sight Guidance

3) Proportional Guidance

A. PURSUIT GUIDANCE

A pursuit guidance law is illustrated in Figure (3-1a) and is one in which the missile velocity vector is always directed toward the target. The target and the missile velocity vectors must therefore be sensed; so this type of guidance normally assumes an on-board tracker. The missile may have a separate mid-course guidance package to increase range, but target lock-on initiates the pursuit guidance for the terminal homing phase.

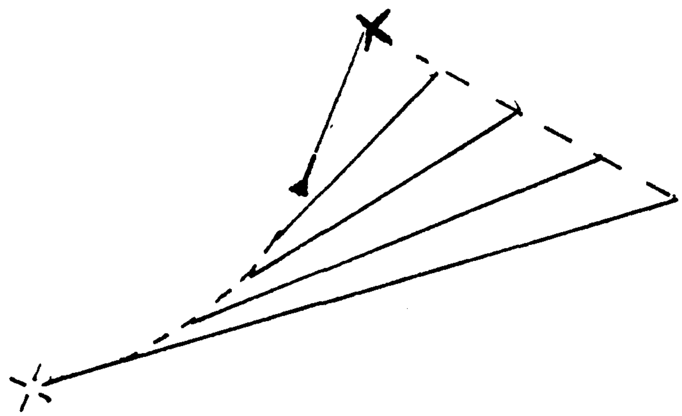


Figure (3-1a). Pursuit guidance.

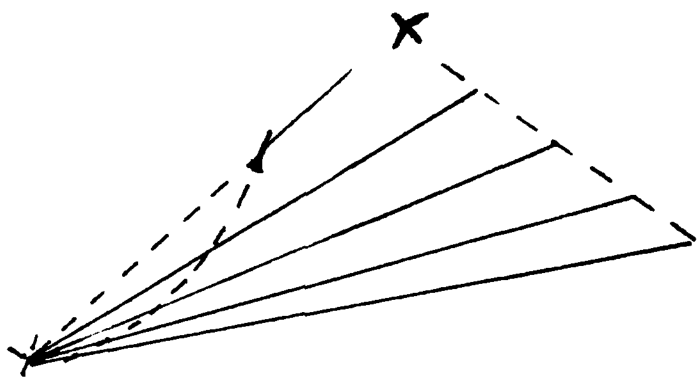


Figure (3-1b). Beam rider guidance.

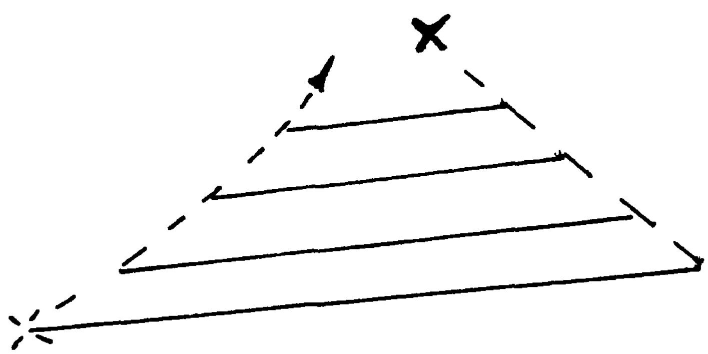


Figure (3-1c). Proportional guidance.

For this reason it has the advantage of launch-and-forget at lock-on. Since the signal processing is limited to looking and pointing, the avionics are relatively simple and usually on-board the missile. An option for this type of guidance would be to include a lead angle to accomodate faster moving targets.

B. LINE-OF-SIGHT GUIDANCE

Line-of-sight guidance is used in a beam rider missile. This guidance scheme is illustrated in Figure (3-1b) and requires that the missile remain on a line (beam) joining the target and a control point. The target tracker is located at the control point; therefore, avoiding the necessity of an on-board tracker. Because of this, a dedicated fire control system is needed from launch to intercept. The range of this type of guidance is normally less than with the other types. A speed advantage is required for line-of-sight guidance since no lead angle is incorporated. The main advantage of this type of guidance is the simple avionics required to maintain the missile in the beam.

C. PROPORTIONAL GUIDANCE

A proportional guidance law is one in which the rate of change of the missile heading is made proportional to the rate of change of the line-of-sight between the missile and the target. This is illustrated in Figure (3-1c). Since the guidance law anticipates the target's future position, it can attain a higher degree of responsiveness than other guidance laws. In proportional guidance the rate of change of the line-of-sight must be sensed on-board the missile. Because of this requirement, and the need to provide anticipated steering commands, the avionics required are the most complex of the three guidance systems.

D. COMPARISON OF GUIDANCE LAWS

In early design considerations two parameters of interest are acceleration required of the missile and the miss distance attainable. Of the three guidance laws only the proportional law can respond to fast maneuvering targets. Since the missile must stay in the line-of-sight for a beam rider system, any target maneuver will cause large excursions in the missile flight path, resulting in large normal accelerations. The pursuit guidance law causes similar large excursions near intercept due to the velocity vector always pointing at the target.

Several system parameters affect the miss distance attainable with a particular guidance law. An excellent source on the effects of these parameters is an article written by Dr. Robert Goodstein[6]. The parameters studied for their effect on miss distance were:

1) Sensor Bias Angle
2) Noise
3) Target Heading
4) Target Acceleration
5) Target Speed
6) Wind Gusts

The results have been reproduced and are included in Figures (3-2) through (3-7). Table 3-I provides overall guidance in the selection of a guidance law and is also reproduced from the above reference. A first glance would indicate that proportional guidance is a proper choice for all cases. It must be kept in mind, though, that cost and simplicity are also driving factors in the design process. Furthermore, it can be seen that, while proportional guidance with a high gain has good performance against maneuvering targets, any noise in the system will highly degrade this performance. For this reason another guidance law may be desired, or a compromise in the gain selection may have to be made in which some performance is given up in order to deal with a noisy system. A reasonable range of proportionality constants that gives good performance against both maneuvering targets and noisy systems is $k = 2$ to $k = 6$.

Once a guidance law is selected, a more detailed analysis has to be performed to determine if the maximum acceleration required of that particular guidance system is within the attainable maneuverability limits for the missile. The maximum acceleration required, in turn, determines the lifting surface area needed. A good estimate of maximum acceleration, which keeps the miss distance less than 50 feet, is to set it equal to three times the target acceleration plus ten.

$$a_m = 3a_t + 10$$

Figure (3-8) shows the miss distance sensitivity to target acceleration.

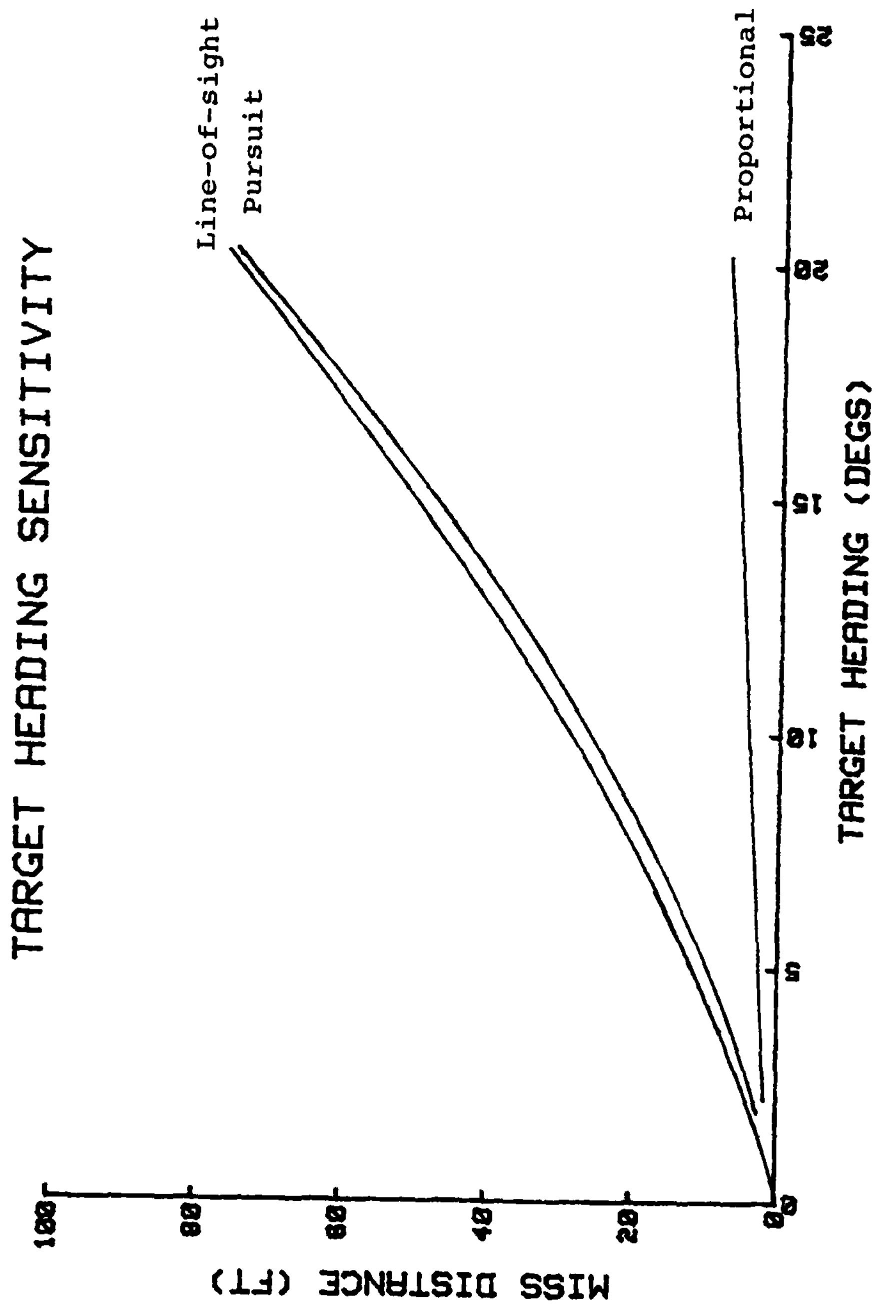

TARGET HEADING SENSITIVITY
MISS DISTANCE (FT)
TARGET HEADING (DEGS)
Line-of-sight
Pursuit
Proportional
0
20
40
60
80
100
5
10
15
20
25

Figure (3-2)

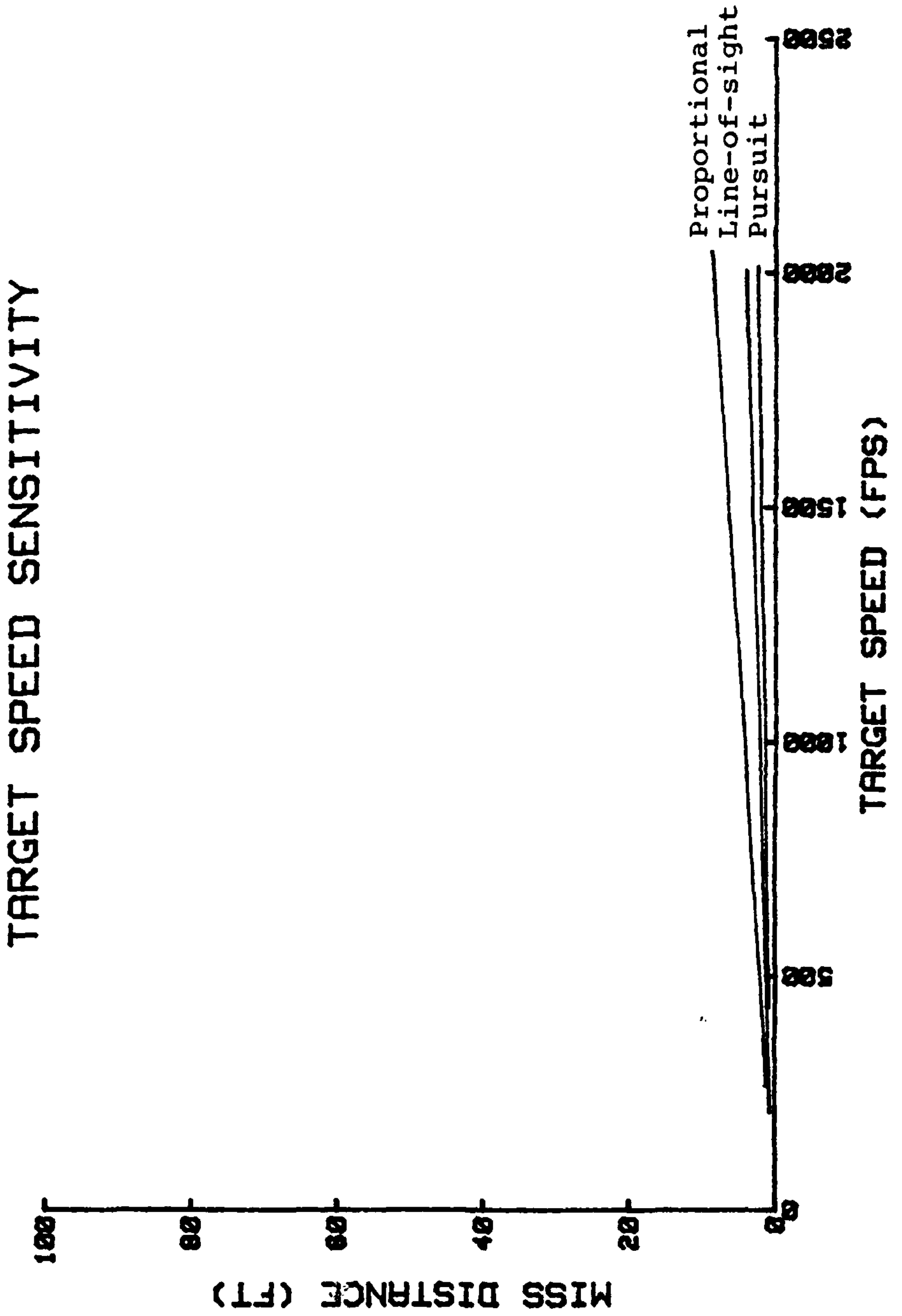

TARGET SPEED SENSITIVITY
MISS DISTANCE (FT)
100
80
60
40
20
0
0
500
1000
1500
2000
2500
TARGET SPEED (FPS)
Proportional
Line-of-sight
Pursuit

Figure (3-3)

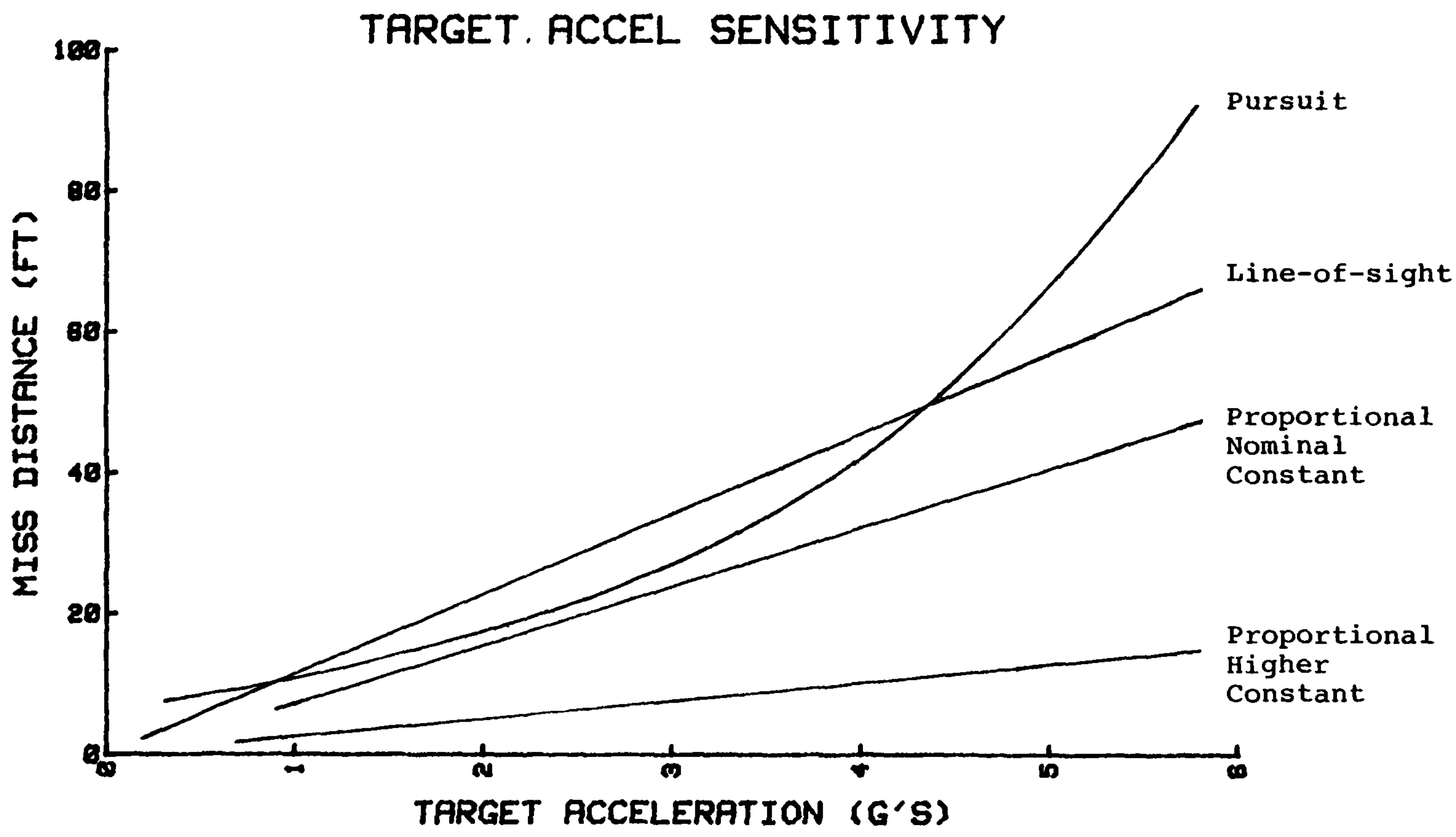

TARGET ACCEL SENSITIVITY
MISS DISTANCE (FT)
TARGET ACCELERATION (G'S)
0
20
40
60
80
100
0
1
2
3
4
5
6
Pursuit
Line-of-sight
Proportional
Nominal
Constant
Proportional
Higher
Constant

Figure (3-4)

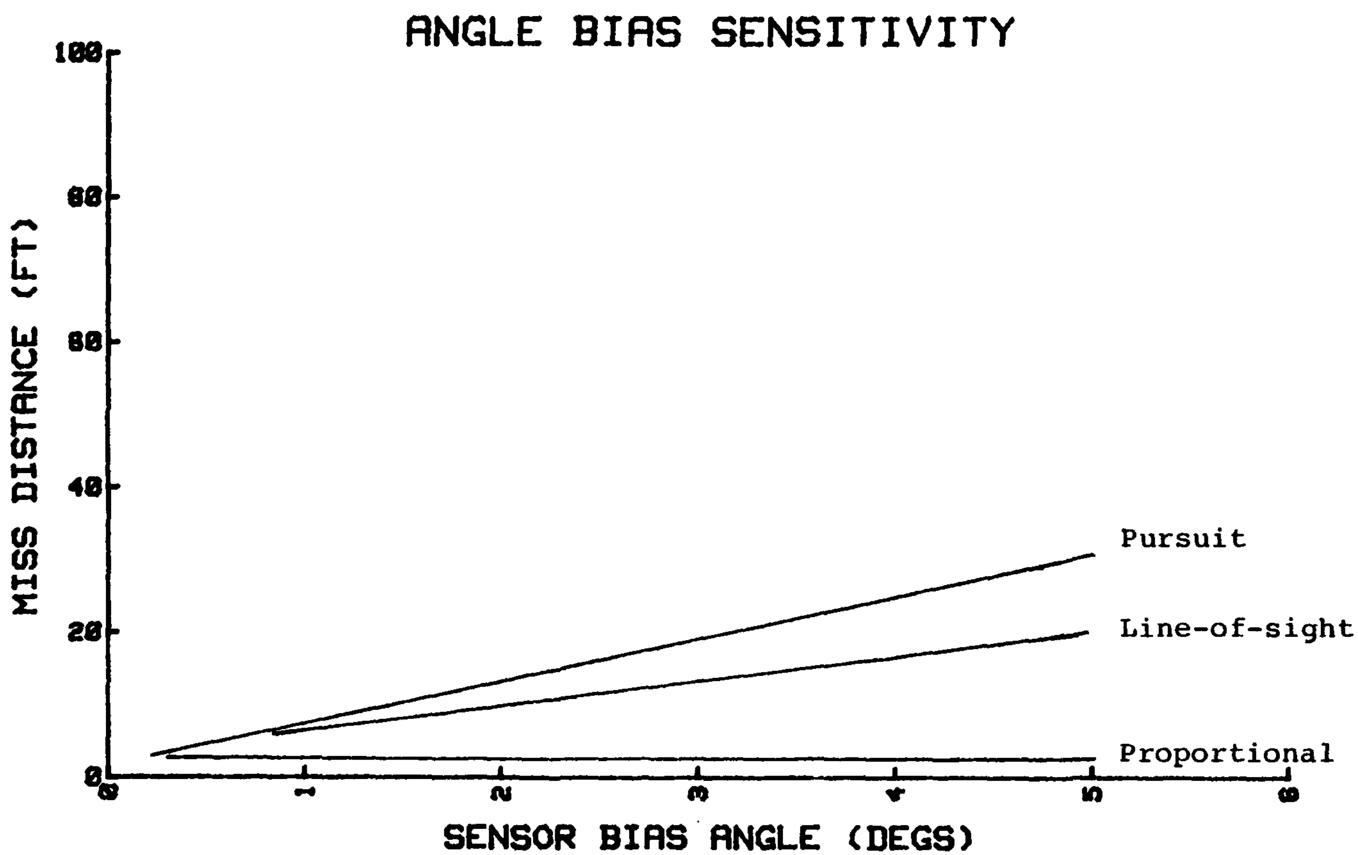

ANGLE BIAS SENSITIVITY
MISS DISTANCE (FT)
100
80
60
40
20
0
0
1
2
3
4
5
6
SENSOR BIAS ANGLE (DEGS)
Pursuit
Line-of-sight
Proportional

Figure (3-5)

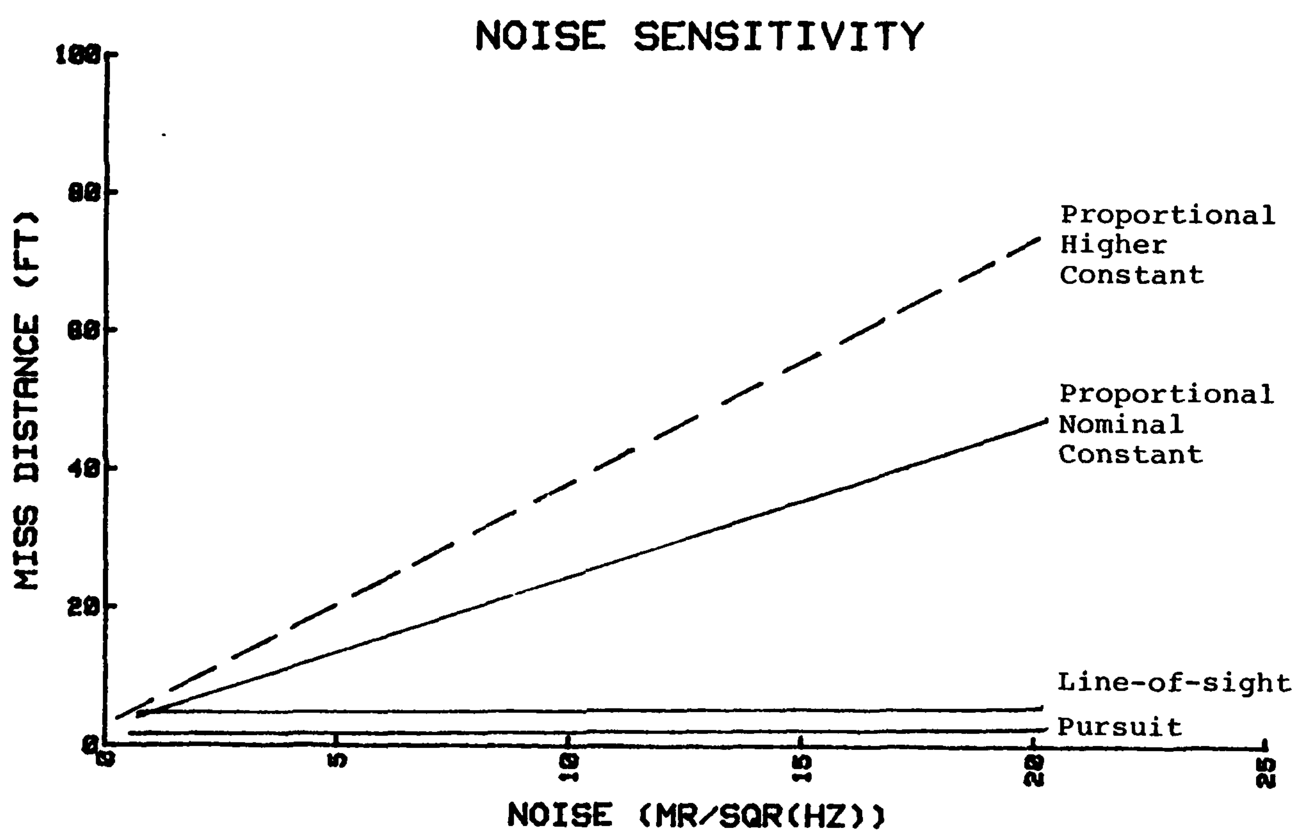

NOISE SENSITIVITY
MISS DISTANCE (FT)
100
80
60
40
20
0
0
5
10
15
20
25
NOISE (MR/SQR(HZ))
Proportional
Higher
Constant
Proportional
Nominal
Constant
Line-of-sight
Pursuit

Figure (3-6)

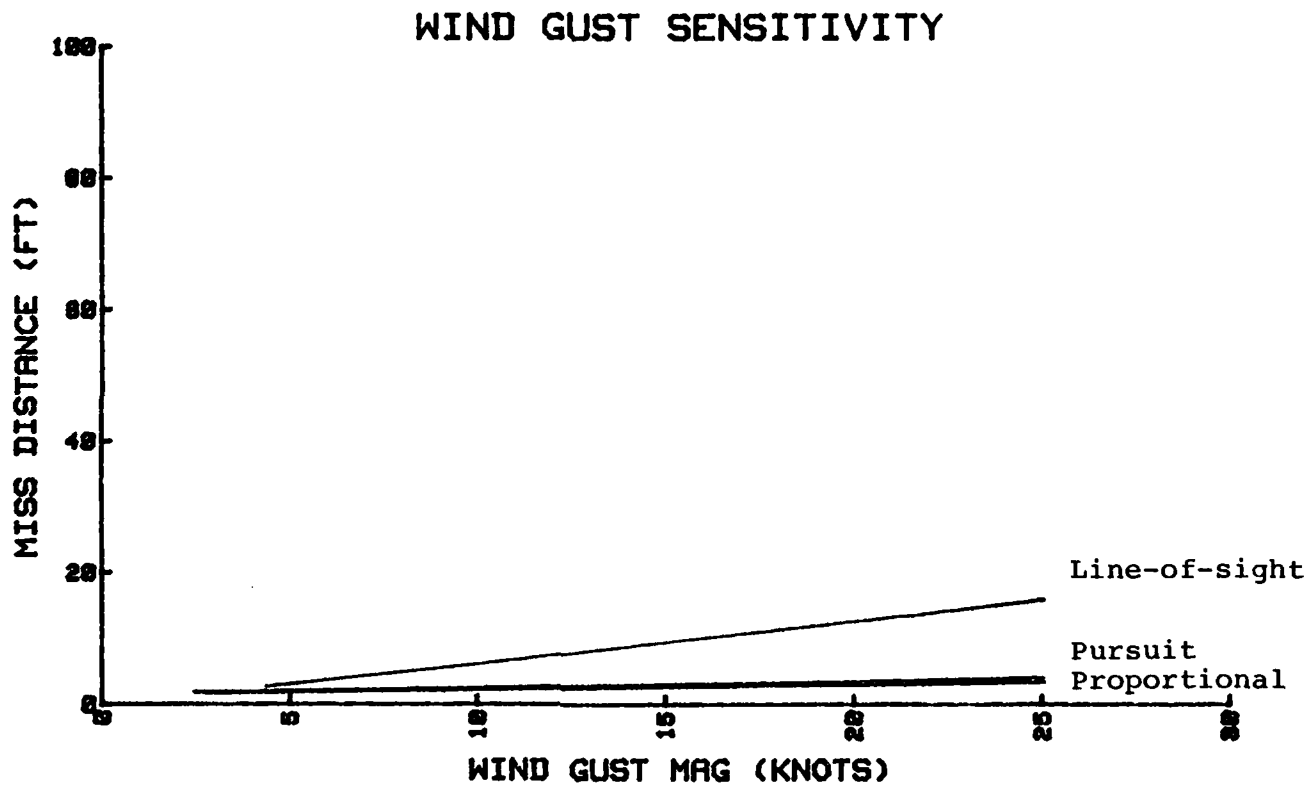

WIND GUST SENSITIVITY
100
80
60
40
20
0
MISS DISTANCE (FT)
0
5
10
15
20
25
30
WIND GUST MAG (KNOTS)
Line-of-sight
Pursuit
Proportional

Figure (3-7)

TABLE 3-I

GUIDANCE LAW TRENDS FOR AIR TARGETS

		Target Heading	Target Speed	Target Accel- eration	Sensor Angle Bias	Noise	Wind Gusts
Line-of-sight	Good		✓			✓	
	Average				✓		✓
	Poor	✓		✓			
Pursuit	Good		✓			✓	✓
	Average				✓		
	Poor	✓		✓			
Propor- tional	Good	✓	✓	✓	✓		✓
	Average						
	Poor					✓	

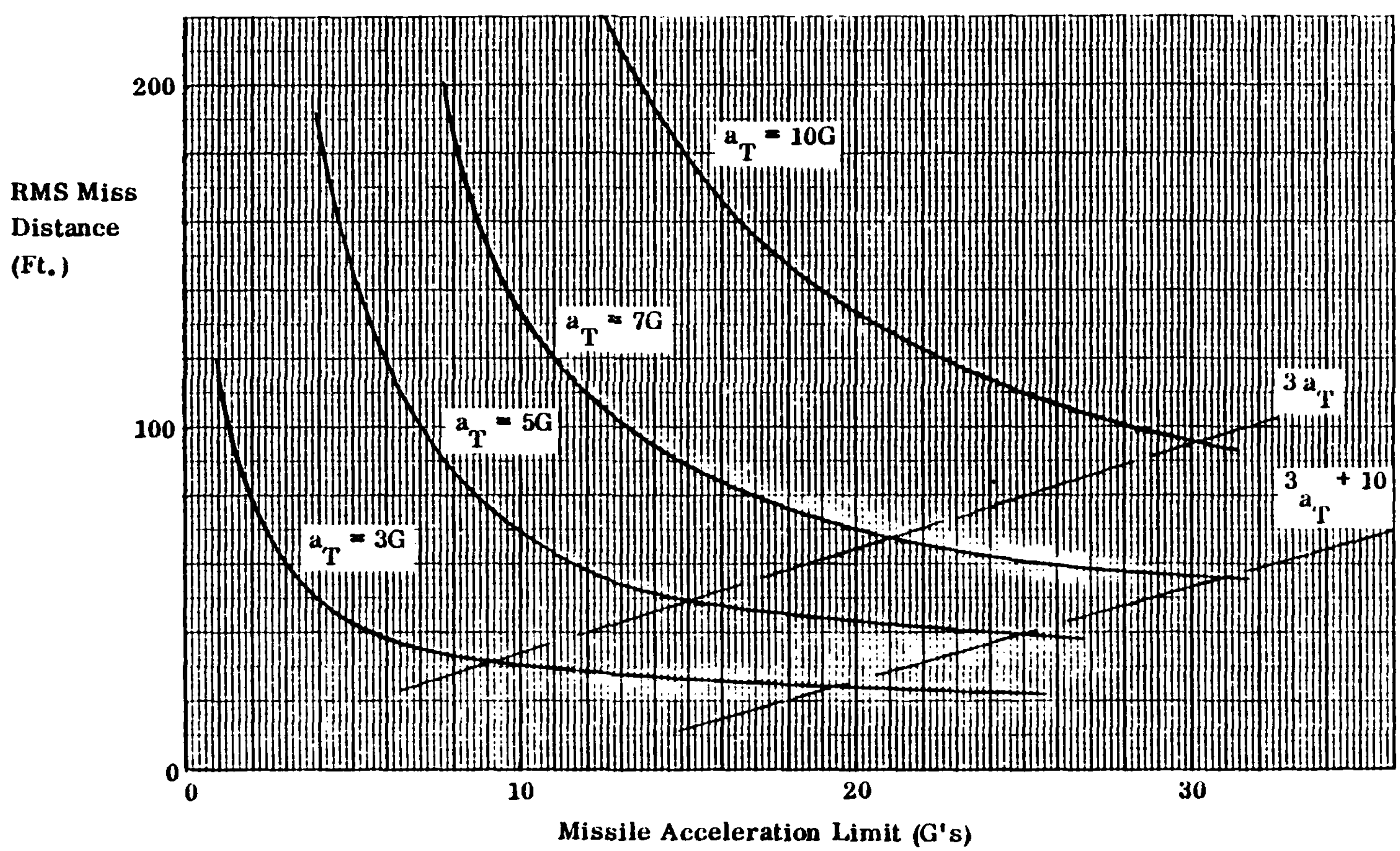


Figure (3-8). Missile acceleration limit [7].

E. PURSUIT GUIDANCE (DETAILED ANALYSIS)

As stated previously, a pursuit guidance law requires the missile velocity vector to always point at the target. For this reason the missile always ends up in a tail chase situation, with the maximum acceleration occurring at the end of the encounter. From this description the maximum acceleration of the missile can be determined.

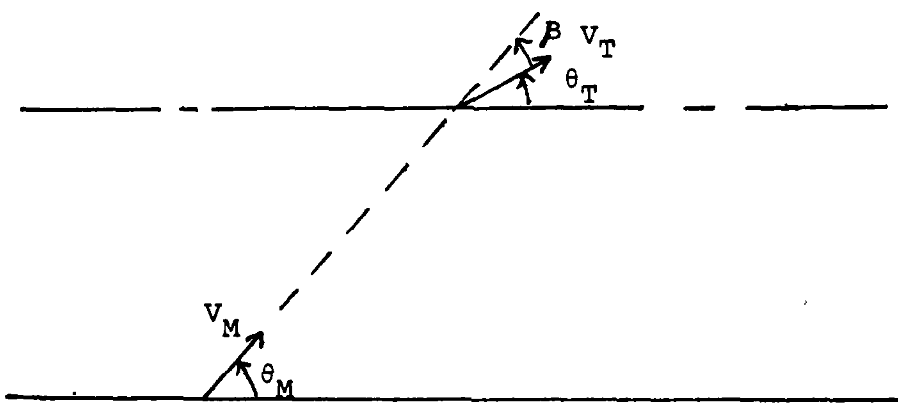


Figure (3-9). Pursuit geometry.

From Figure (3-9) the time rate of change of the range, R, is

$$\dot{R} = V_T \cos \beta - V_M$$

also

$$\dot{\beta} = -V_T \sin \beta / R$$

or

$$R \frac{d\beta}{dt} = V_T \sin \beta$$

$$\frac{d\beta}{\sin\beta} = -\frac{V_T}{R}\,dt \qquad (1)$$

$$dt = \frac{dR}{V_T\cos\beta - V_M} \qquad (2)$$

Substituting equation (2) into equation (1) gives,

$$\frac{d\beta}{\sin\beta} = -\frac{V_T}{R}\,\frac{dR}{(V_T\cos\beta - V_M)}\,; \quad \text{Letting } k = \frac{V_M}{V_T}$$

$$\frac{(\cos\beta - k)}{\sin\beta}\,d\beta = -\frac{dR}{R} \qquad (3)$$

Integrating equation (3) yields,

$$\ell nR = k\ell n(\tan\frac{\beta}{2}) - \ell n(\sin\beta) + \ell nc_1$$

$$\ell nR = \ell n\left[\frac{c_1\ \tan^k\beta/2}{\sin\beta}\right]$$

By trigonometric identity,

$$(\tan\beta/2)^k = \frac{(\sin\beta)^k}{(1+\cos\beta)^k}$$

Therefore,

$$\ell nR = \ell n\left[\frac{c_1\ (\sin\beta)^{k-1}}{(1+\cos\beta)^k}\right]$$

and

$$R = \frac{c_1\ (\sin\beta)^{k-1}}{(1+\cos\beta)^k}$$

From the initial condition $\beta = \beta_0$ when $R = R_0$,

$$c_1 = \frac{R_o \ (1+\cos\beta_0)^k}{(\sin\beta_0)^{k-1}}$$

$$R = R_0 \left(\frac{1+\cos\beta_0}{1+\cos\beta}\right)^k \left(\frac{\sin\beta}{\sin\beta_0}\right)^{k-1}$$

Substituting the above equation for R into the equation for $\dot{\beta}$

$$\dot{\beta} = -V_t \ \sin\beta/R$$

$$\dot{\beta} = -\frac{V_t}{R_0} \left(\frac{1+\cos\beta}{1+\cos\beta_0}\right)^k \frac{(\sin\beta)^{2-k}}{(\sin\beta_0)^{1-k}}$$

The missile acceleration can be expressed as a normal and a tangential component,

$$\bar{a} = V_M \ \dot{\beta} \ \hat{n} + \dot{V}_M \ \hat{t}$$

The normal component is a_m, where,

$$a_m = V_M \ \dot{\beta}$$

$$a_m = -\frac{V_M V_T}{R_0} \left(\frac{1+\cos\beta}{1+\cos\beta_0}\right)^k \frac{\sin\beta}{\sin\beta_0} \begin{matrix} 2-k \\ 1-k \end{matrix}$$

The terminal acceleration for a pursuit guidance law will occur at the end of the encounter ($\beta \rightarrow 0$). From the above expression the terminal acceleration can be evaluated

$$a_m = 0, \quad \text{for} \quad 1 < k < 2$$

$$a_m = -\frac{V_M V_T}{R_0} \left(\frac{2}{1+\cos\beta_0} \right)^2 \sin\beta_0 \quad \text{for} \quad k = 2$$

$$a_m = \infty \quad \text{for} \quad k > 2$$

Since pursuit guidance always ends up in a tail chase situation, the missile will never intercept if $k < 1$. Thus, for pursuit guidance operating against a non-maneuvering target, the velocity ratio should be between one and two. These results indicate this guidance system would not be effective against air targets; therefore, results for a maneuvering target were not pursued.

F. LINE-OF-SIGHT GUIDANCE (DETAILED ANALYSIS)

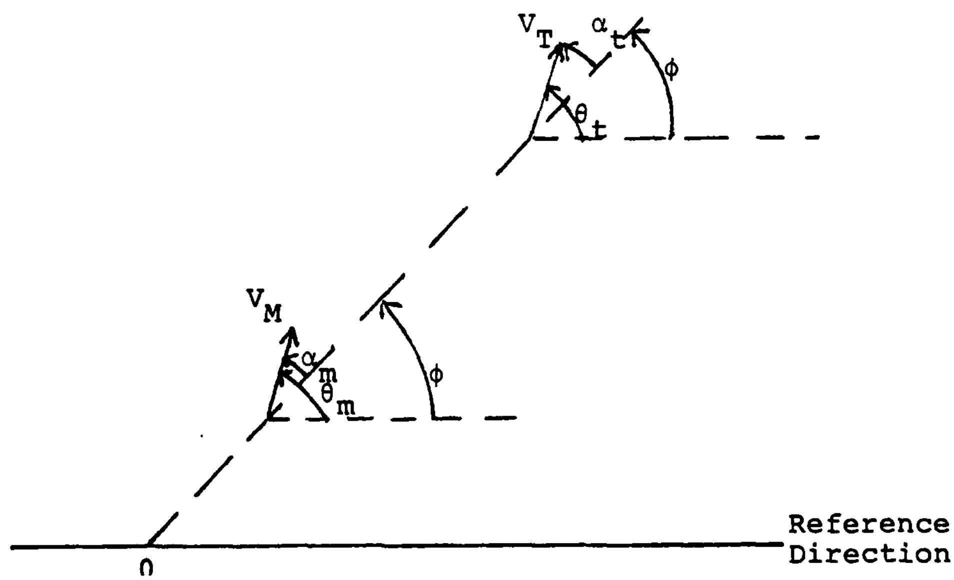


Figure (3-10). Line-of-sight geometry.

Figure (3-10) illustrates the geometry used to derive the beam rider equations of motion. The basic concept of beam rider guidance is that the missile is maintained in the line-of-sight of the target and a control point. This can be expressed in an equation as follows:

$$\dot{\phi} = \frac{V_T \sin \alpha_t}{r_t} = \frac{V_M \sin \alpha_m}{r_m} \tag{1}$$

where, r_t = range from point 0 to the target

r_m = range from point 0 to the missile

From equation (1)

$$r_t V_M \sin \alpha_m = r_m V_T \sin \alpha_t \tag{2}$$

As in the case of pursuit guidance, the missile and target accelerations can be divided into normal and tangential components. If the target is limited to contant g turns, and the normal component of missile acceleration is of interest; then,

$$\dot{V}_T = \dot{V}_M = 0$$

Differentiating equation (2) with respect to time yields,

$$\dot{r}_t V_M \sin \alpha_m + r_t\, V_M\, \dot{\alpha}_m \cos \alpha_m = \dot{r}_m\, V_T \sin \alpha_t + V_T\, \dot{\alpha}_t \cos \alpha_t$$

Solving for $\dot{\alpha}_m$,

$$\dot{\alpha}_m = \frac{1}{r_t V_M \cos\alpha_m} [\dot{r}_m\, V_T \sin \alpha_t + r_m\, V_T\, \dot{\alpha}_t \cos \alpha_t - \dot{r}_t\, V_M \sin \alpha_m]$$

From the original figure,

$$\dot{r}_t = V_T \cos \alpha_t$$

$$\dot{r}_m = V_M \cos \alpha_m$$

Also

$$\theta_t = \alpha_t + \phi \longrightarrow \dot{\theta}_t = \dot{\alpha}_t + \dot{\phi}$$

$$\theta_m = \alpha_m + \phi \longrightarrow \dot{\theta}_m = \dot{\alpha}_m + \dot{\phi}$$

The target and missile accelerations (normal components) become,

$$a_t = V_T \dot{\theta}_t$$

$$a_m = V_M \dot{\theta}_m$$

Collecting equations;

$$\dot{\theta}_t = a_t/V_t$$

$$\dot{\phi} = V_T \sin \alpha_t/r_t$$

$$\dot{\alpha}_t = \dot{\theta}_t - \dot{\phi}$$

$$\dot{r}_t = V_T \cos \alpha_t$$

$$\dot{r}_m = V_M \cos \alpha_m$$

$$\dot{\alpha}_m = \frac{1}{r_t V_M \cos\alpha_m}\left[\dot{r}_m V_T \sin \alpha_t + r_m V_T \dot{\alpha}_t \cos \alpha_t - \dot{r}_t V_M \sin \alpha_m\right]$$

$$\dot{\theta}_m = \dot{\alpha}_m + \dot{\phi}$$

$$a_m = V_M \dot{\theta}_m$$

The above equations are the equations of motion which describe the target and missile trajectories. These equations cannot be solved analytically except for highly specialized cases. The complete set of equations can be solved using a numerical integration technique. If Euler's one step method is used, the algorithm is as follows;

$$\theta_t(i+1) = \theta_t(i) + \Delta t\ \dot{\theta}_t(i)$$

$$\phi(i+1) = \phi(i) + \Delta t\ \dot{\phi}(i)$$

$$\alpha_t(i+1) = \alpha_t(i) + \Delta t\ \dot{\alpha}_t(i)$$

$$r_t(i+1) = r_t(i) + \Delta t\ \dot{r}_t(i)$$

$$r_m(i+1) = r_m(i) + \Delta t\ \dot{r}_m(i)$$

$$\alpha_m(i+1) = \alpha_m(i) + \Delta t\ \dot{\alpha}_m(i)$$

$$\theta_m(i+1) = \theta_m(i) + \Delta t\ \dot{\theta}_m(t)$$

With initial conditions;

$$r_t(0) = r_0$$

$$r_m(0) = 0$$

$$\phi(0) = \phi_0$$

$$\alpha_m(0) = 0$$

$$\theta_t(0) = \theta_{t_0}$$

$$\theta_m(0) = \theta_{m_0}$$

$$\alpha_t(0) = \alpha_{t_0}$$

The target and missile positions can be expressed as follows;

$$x_m(i+1) = x_m(i) + \Delta t\ V_M \cos\theta_m(i)$$

$$y_m(i+1) = y_m(i) + \Delta t\ V_M \sin\theta_m(i)$$

$$x_t(i+1) = x_t(i) + \Delta t\ V_T \cos\theta_t(i)$$

$$y_t(i+1) = y_t(i) + \Delta t\ V_T \sin\theta_t(i)$$

Where

$$x_m(0) = y_m(0) = 0$$

$$y_t(0) = r_0 \cos\phi_0$$

$$y_t(0) = r_0 \sin\phi_0$$

The above equations have been programmed on the HP 9830 computer. Table 3-II is a listing of this program. The program asks the user for the initial conditions and the target acceleration. It also asks for the integration step increment, Δt. It should be kept in mind when using the program that the error involved in integrating is of order Δt. The output is a plot of missile and target trajectories as well as the missile maximum acceleration and time of flight. Three examples follow which demonstrate possible uses of the program. (Note: All angles are input in radians.)

TABLE 3-II

```
10 PRINT "THIS PROGRAM DETERMINES THE ACCELARATION OF"
20 PRINT "A BEAM RIDER MISSILE AND PLOTS THE TRAJECTORY"
30 PRINT
40 PRINT "INPUT TIME INCREMENT FOR INTEGRATION"
50 INPUT D1
60 DIM X[250],Y[250],U[250],V[250],A[250],R[250]
70 PRINT "INPUT INITIAL TARGET RANGE"
80 INPUT R1
90 PRINT "INPUT TARGET SPEED"
100 INPUT V1
110 PRINT "INPUT MISSILE SPEED"
120 INPUT V2
130 PRINT "INPUT INITIAL LINE OF SIGHT ANGLE"
140 INPUT P1
150 PRINT "INPUT MISSILE ALPHA"
160 INPUT A2
170 PRINT "INPUT TARGET ALPHA"
180 INPUT A1
190 PRINT "INPUT MISSILE THETA"
200 INPUT T2
210 PRINT "INPUT TARGET THETA"
220 INPUT T1
230 PRINT "INPUT TARGET ACCELERATION"
240 INPUT G1
250 I=1
260 R2=0
265 R[1]=R1
270 A[1]=0
280 X[I]=0
290 Y[I]=0
300 U[I]=R1*COS(P1)
310 V[I]=R1*SIN(P1)
320 A[I]=0
330 PRINT "    XM                YM                    XT            YT
395 PRINT "DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO"
396 INPUT T9
397 IF T9=1 THEN 410
400 PRINT X[I],Y[I],U[I],V[I]
410 I=I+1
420 T3=G1/V1
430 P3=V1*SIN(A1)/R1
440 A3=T3-P3
450 R3=V1*COS(A1)
460 R4=V2*COS(A2)
461 D6=R4*V1*SIN(A1)
462 D7=R2*V1*A3*COS(A1)
463 D8=-R3*V2*SIN(A2)
464 D9=R1*V2*COS(A2)
```

TABLE 3-II (cont)

```
465 A4=(D6+D7+D8)/D9
466 T4=A4+P3
470 T1=T1+D1*T3
480 P1=P1+D1*P3
490 A1=A1+D1*A3
495 R1=R1+D1*R3
496 R2=R2+D1*R4
500 A2=A2+D1*A4
510 T2=T2+D1*T4
520 A[I]=V2*T4
530 IF ABS(A[I])<ABS(A[I-1]) THEN 600
540 M=A[I]
600 T2=A2+P1
610 R[I]=R1-R2
620 X[I]=X[I-1]+D1*V2*COS(T2)
630 Y[I]=Y[I-1]+D1*V2*SIN(T2)
640 U[I]=U[I-1]+D1*V1*COS(T1)
650 V[I]=V[I-1]+D1*V1*SIN(T1)
660 IF R[I]>0 THEN 397
665 T5=D1*(I-1)
670 PRINT "INPUT MINIMUM X VALUE"
680 INPUT X6
690 PRINT "INPUT MAXIMUM X VALUE"
700 INPUT X7
710 PRINT "INPUT MINIMUM Y VALUE"
720 INPUT Y6
730 PRINT "INPUT MAXIMUM Y VALUE"
740 INPUT Y7
800 SCALE X6,X7,Y6,Y7
810 PRINT "HAS AXIS BEEN DRAWN, 0=YES, 1=NO"
820 INPUT F1
830 IF F1=0 THEN 860
840 XAXIS 0,X7/10
850 YAXIS 0,Y7/10
860 PEN
870 FOR W=1 TO I
880 PLOT X[W],Y[W]
890 NEXT W
900 PEN
910 FOR S=1 TO I
920 PLOT U[S],V[S]
930 NEXT S
940 PEN
950 PRINT
951 PRINT
952 IF A[I]>A[I-1] THEN 954
953 M=A[I-1]
954 PRINT "THE MAXIMUM ACCELERATION IS   "M"  METERS/SEC/SEC"
960 PRINT "THE TIME TO  INTERCEPT IS   "T5"  SEC"
1000 STOP
```

1. <u>Example I (Non-maneuvering Crossing Target)</u>

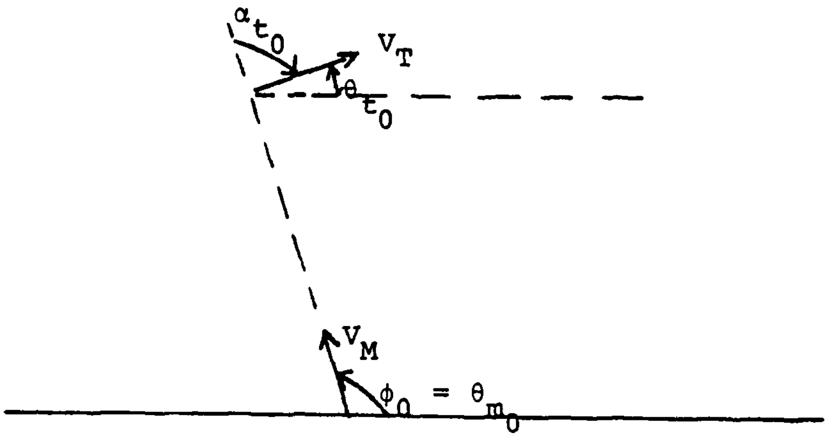


Figure (3-11). Non-maneuvering crossing geometry.

r_0 = 359 meters

$\phi_0 = 109.57^{\circ} = 1.9124$ rad

$\theta_{t_0} = 17.57^{\circ} = .3067$ rad

$\theta_{m_0} = 109.57^{\circ} = 1.9124$ rad

$\alpha_{t_0} = -91.0^{\circ} = 01.5882$ rad

$a_t = 0$

V_M = 373 m/sec

V_T = 221 m/sec

Table 3-III is the computer output. As indicated the missile maximum acceleration is,

$$a_m = -459.25 \text{ m/sec/sec} = -46.86 \text{ g's}$$

TABLE 3-III

```
INPUT TIME INCREMENT FOR INTEGRATION
INPUT INITIAL TARGET RANGE
INPUT TARGET SPEED
INPUT MISSILE SPEED
INPUT INITIAL LINE OF SIGHT ANGLE
INPUT MISSILE ALPHA
INPUT TARGET ALPHA
INPUT MISSILE THETA
INPUT TARGET THETA
INPUT TARGET ACCELERATION
   XM              YM              XT              YT
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO
 0              0              -120.2644734    338.256495
-5.154984716    17.92341018    -109.7301208    341.5926479
-9.197499767    36.1300181     -99.19576818    344.9288007
-12.11631881    54.55019713    -88.66141559    348.2649534
-13.90888092    73.11385036    -78.127063      351.6011062
-14.58120543    91.75172791    -67.5927104     354.937259
-14.14756982    110.3966859    -57.05835782    358.2734118
-12.62997166    128.9848380    -46.52400523    361.6095646
-10.0574058     147.456557     -35.98965264    364.9457174
-6.464996448    165.7572973    -25.45530005    368.2818702
-1.893028052    183.8382156    -14.92094745    371.618023
 3.614079320    201.6565844    -4.386594863    374.9541758
 10.00880633    219.1760013     6.147757728    378.2903286
 17.24154285    236.3664062     16.68211032    381.6264814
 25.26153519    253.2039305     27.21646291    384.9626342
 34.01774632    269.6706019     37.7508155     388.298787
 43.45961099    285.7539377     48.28516809    391.6349398
 53.53767559    301.4464555     58.81952068    394.9710926
 64.2041194     316.745131      69.35387327    398.3072454
 75.41315987    331.6508318     79.88822587    401.6433982
 87.12134900    346.1677463     90.42257846    404.979551
 99.28777153    360.3028325     100.956931     408.3157038
 111.8741571    374.0652959     111.4912836    411.6518566
 124.8449199    387.4661097     122.0256362    414.9880094
 138.1671393    400.5175836     132.5599888    418.3241622
 151.8104937    413.232983      143.0943414    421.660315
INPUT MINIMUM X VALUE
INPUT MAXIMUM X VALUE
INPUT MINIMUM Y VALUE
INPUT MAXIMUM Y VALUE
HAS AXIS BEEN DRAWN, 0=YES, 1=NO


THE MAXIMUM ACCELERATION IS   -459.2526072     METERS/SEC/SEC
THE TIME TO  INTERCEPT IS    1.3    SEC
```

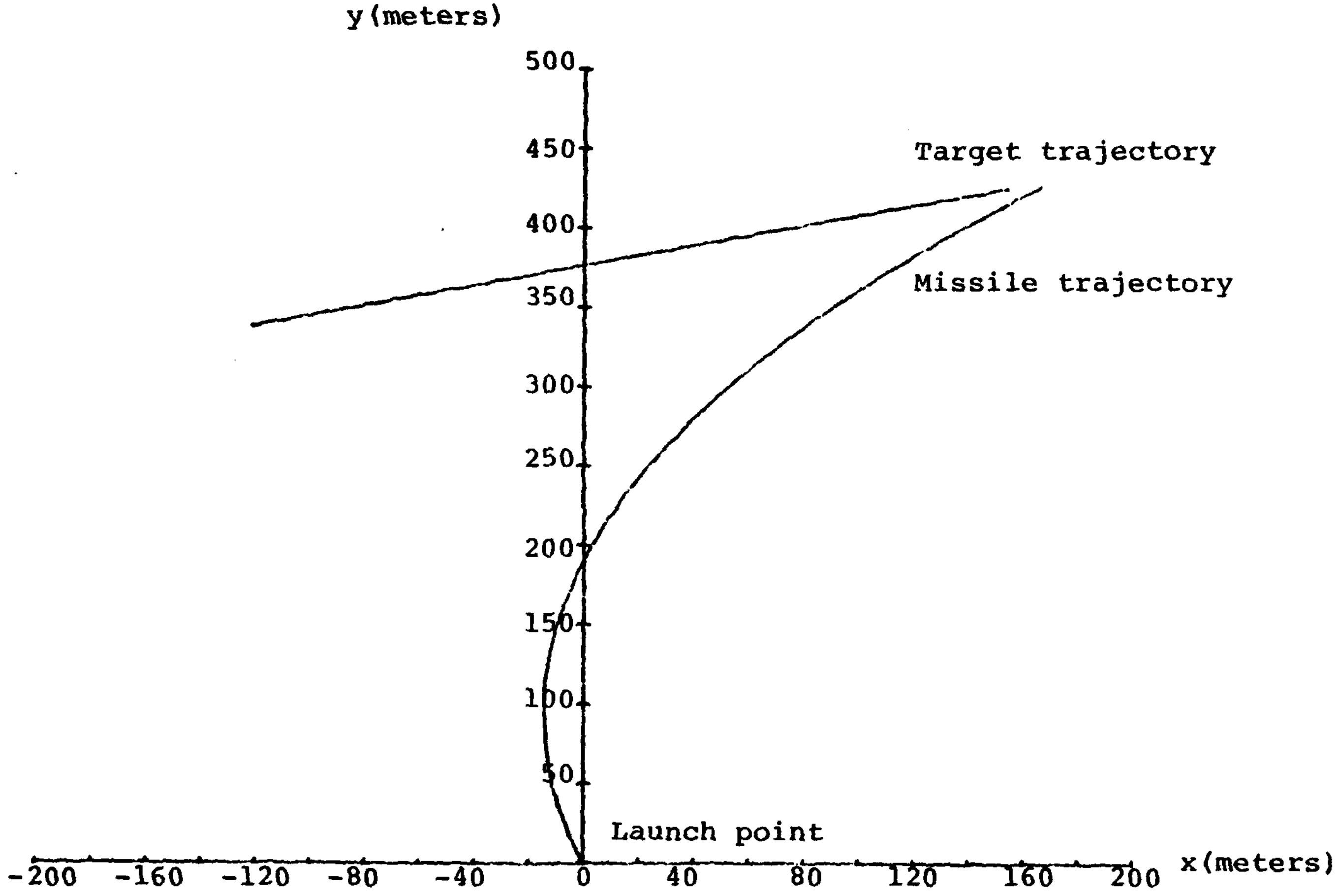


Figure (3-12). Target and missile positions for a non-maneuvering crossing target.

The large acceleration is typical of line-of-sight due to the missile requirement to stay in the beam. The trajectories are plotted in Figure (3-12).

2. Example II (Effect of V_M)

This example is presented to study the effect of missile velocity on a crossing target (non-maneuvering).

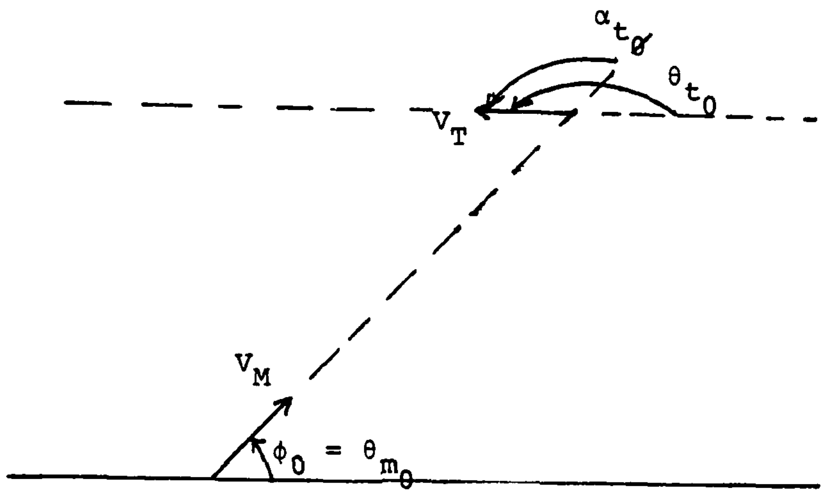


Figure (3-13). Crossing target geometry.

The initial conditions are as follows;

$$r_0 = 4000 \text{ m}$$

$$\phi_0 = 45^\circ = .7854 \text{ rad}$$

$$\theta_{m_0} = 45^\circ = .7854 \text{ rad}$$

$$\alpha_{t_0} = 135^\circ = 2.3562 \text{ rad}$$

$$\theta_{t_0} = 180^\circ = 3.1416 \text{ rad}$$

$$V_T = 200 \text{ m/sec}$$

TABLE 3-IV

```
THIS PROGRAM DETERMINES THE ACCELARATION OF
A BEAM RIDER MISSILE AND PLOTS THE TRAJECTORY

INPUT TIME INCREMENT FOR INTEGRATION
INPUT INITIAL TARGET RANGE
INPUT TARGET SPEED
INPUT MISSILE SPEED = 400 m/SEC
INPUT INITIAL LINE OF SIGHT ANGLE
INPUT MISSILE ALPHA
INPUT TARGET ALPHA
INPUT MISSILE THETA
INPUT TARGET THETA
INPUT TARGET ACCELERATION
   XM               YM                  XT           YT
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO
INPUT MINIMUM X VALUE
INPUT MAXIMUM X VALUE
INPUT MINIMUM Y VALUE
INPUT MAXIMUM Y VALUE
HAS AXIS BEEN DRAWN, 0=YES, 1=NO


THE MAXIMUM ACCELERATION IS    58.03129548     METERS/SEC/SEC
THE TIME TO  INTERCEPT IS    8      SEC


THIS PROGRAM DETERMINES THE ACCELARATION OF
A BEAM RIDER MISSILE AND PLOTS THE TRAJECTORY

INPUT TIME INCREMENT FOR INTEGRATION
INPUT INITIAL TARGET RANGE
INPUT TARGET SPEED
INPUT MISSILE SPEED = 600 m/SEC
INPUT INITIAL LINE OF SIGHT ANGLE
INPUT MISSILE ALPHA
INPUT TARGET ALPHA
INPUT MISSILE THETA
INPUT TARGET THETA
INPUT TARGET ACCELERATION
   XM               YM                  XT           YT
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO
INPUT MINIMUM X VALUE
INPUT MAXIMUM X VALUE
INPUT MINIMUM Y VALUE
INPUT MAXIMUM Y VALUE
HAS AXIS BEEN DRAWN, 0=YES, 1=NO


THE MAXIMUM ACCELERATION IS    72.78774168     METERS/SEC/SEC
THE TIME TO  INTERCEPT IS    5.6    SEC
```

TABLE 3-IV (cont)

```
THIS PROGRAM DETERMINES THE ACCELARATION OF
A BEAM RIDER MISSILE AND PLOTS THE TRAJECTORY

INPUT TIME INCREMENT FOR INTEGRATION
INPUT INITIAL TARGET RANGE
INPUT TARGET SPEED
INPUT MISSILE SPEED = 800 m/SEC
INPUT INITIAL LINE OF SIGHT ANGLE
INPUT MISSILE ALPHA
INPUT TARGET ALPHA
INPUT MISSILE THETA
INPUT TARGET THETA
INPUT TARGET ACCELERATION
   XM              YM                  XT          YT
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO
INPUT MINIMUM X VALUE
INPUT MAXIMUM X VALUE
INPUT MINIMUM Y VALUE
INPUT MAXIMUM Y VALUE
HAS AXIS BEEN DRAWN, 0=YES, 1=NO


THE MAXIMUM ACCELERATION IS    87.22950871     METERS/SEC/SEC
THE TIME TO  INTERCEPT IS    4.4    SEC
```

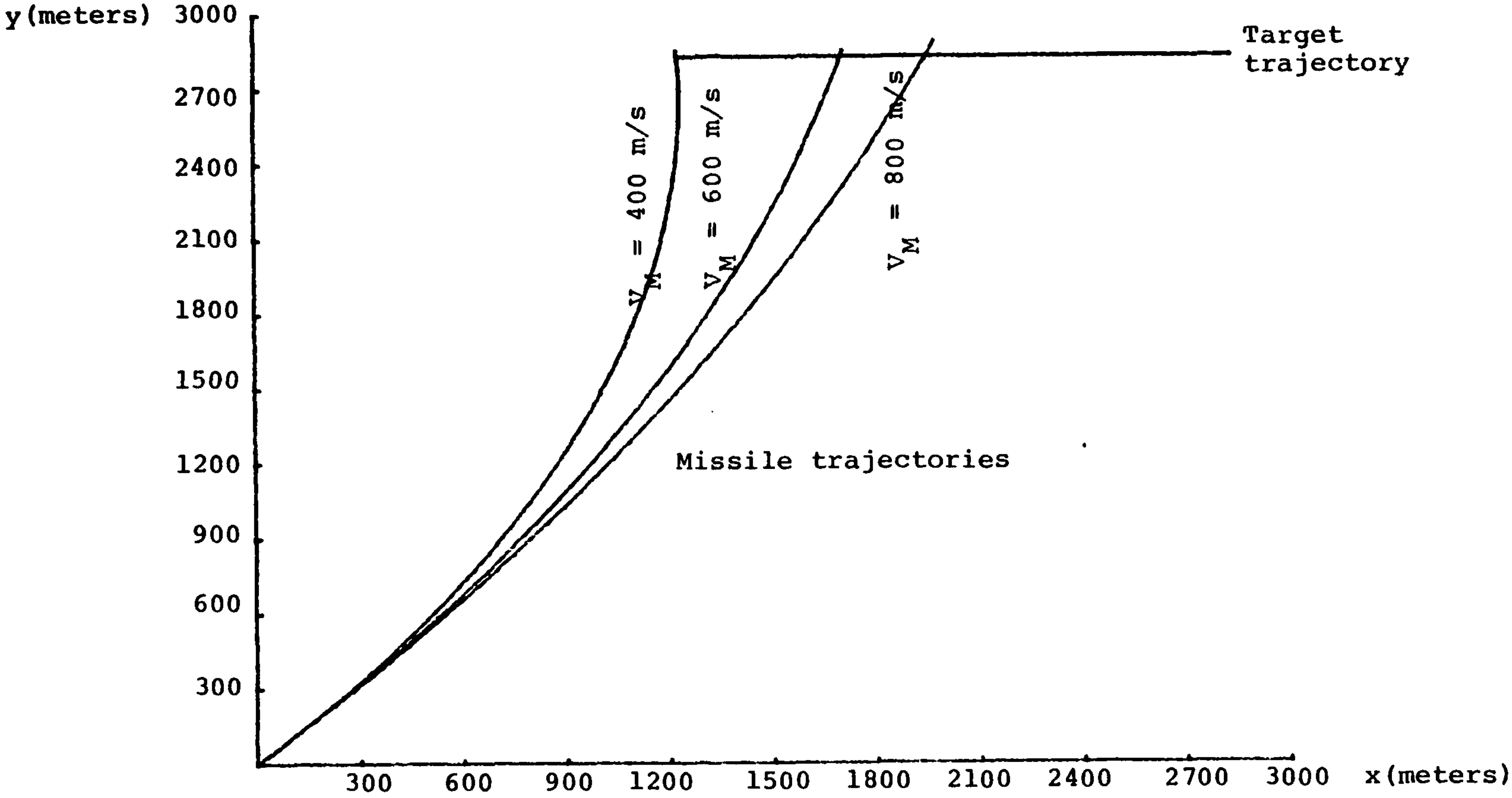


Figure (3-14). Effect of V_M on the encounter.

The program was run three times for a missile velocities of 400, 600, and 800 m/sec. Table 3-IV contains the program outputs and Figure (3-14) is the plot of the trajectories. As can be seen from the output, the missile maximum acceleration increases with increasing missile speed. For example, $V_M/V_T = 2$ gives the smallest acceleration, although the maximum acceleration for $V_M/V_T = 4$ is not exceedingly large for this scenario.

3. Example III (Maneuvering target)

In this example the effect of a target maneuver is investigated. If at the time of launch the target initiates a 7 g (68.6 m/sec/sec) turn, the following encounter would result:

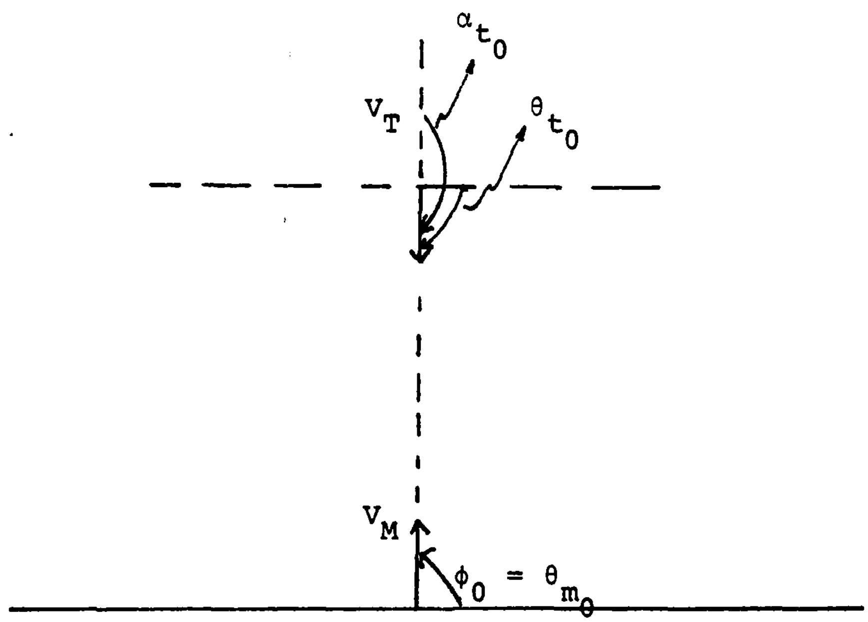


Figure (3-15). Maneuvering target.

TABLE 3-V

```
THIS PROGRAM DETERMINES THE ACCELARATION OF
A BEAM RIDER MISSILE AND PLOTS THE TRAJECTORY

INPUT TIME INCREMENT FOR INTEGRATION
INPUT INITIAL TARGET RANGE
INPUT TARGET SPEED
INPUT MISSILE SPEED
INPUT INITIAL LINE OF SIGHT ANGLE
INPUT MISSILE ALPHA
INPUT TARGET ALPHA
INPUT MISSILE THETA
INPUT TARGET THETA
INPUT TARGET ACCELERATION
   XM              YM              XT          YT
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO
INPUT MINIMUM X VALUE
INPUT MAXIMUM X VALUE
INPUT MINIMUM Y VALUE
INPUT MAXIMUM Y VALUE
HAS AXIS BEEN DRAWN, 0=YES, 1=NO


THE MAXIMUM ACCELERATION IS   -355.8215593     METERS/SEC/SEC
THE TIME TO  INTERCEPT IS    5.8    SEC
```

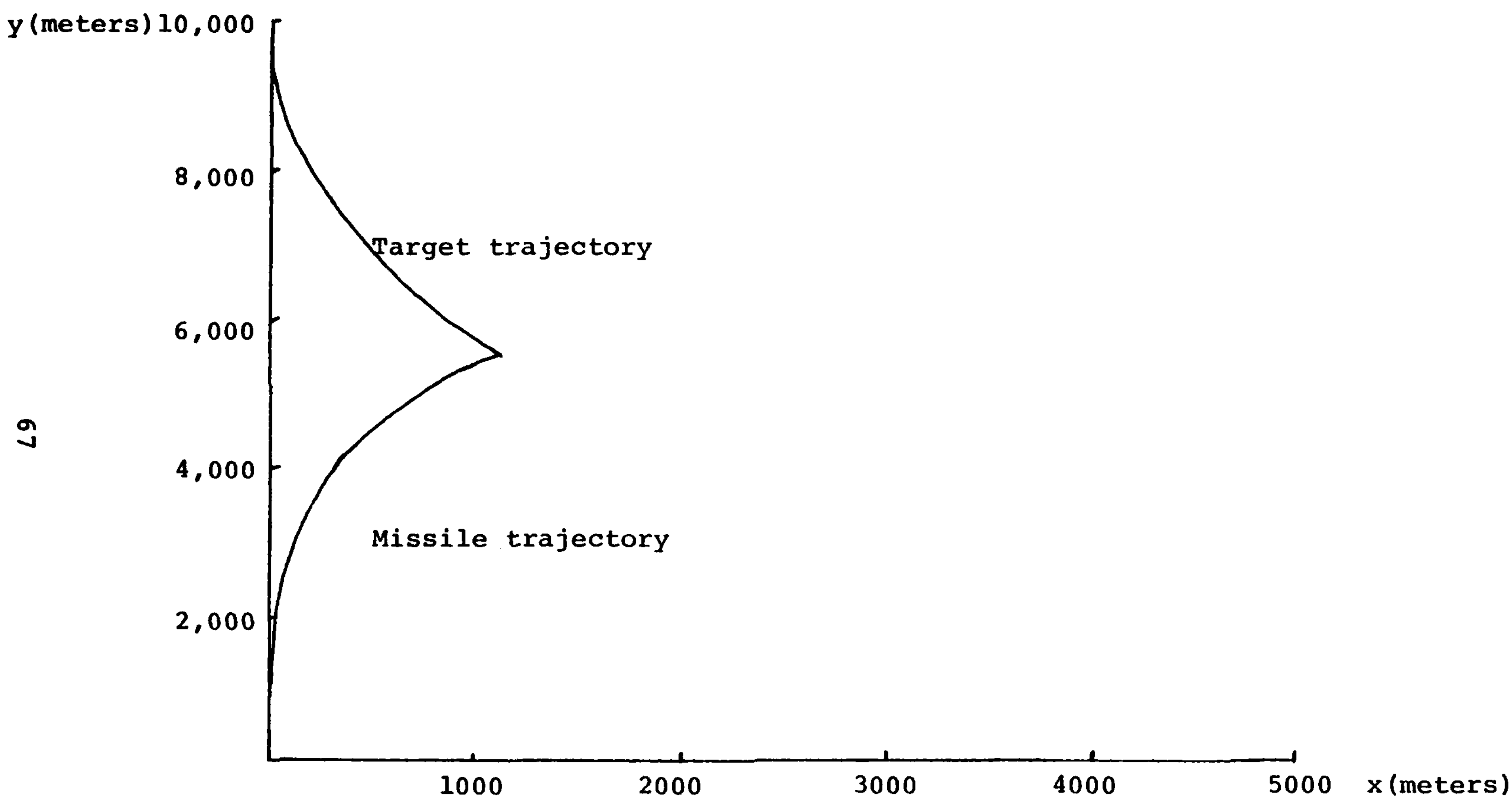


Figure (3-16). Effect of a 7g maneuver upon the encounter.

The initial conditions are;

$r_0 = 10000$ m $\qquad V_T = 821.436$ m/sec

$\phi_0 = 90^\circ = 1.5708$ rad $\qquad V_M = 985.723$ m/sec

$\theta_{m_0} = 90^\circ = 1.5708$ rad

$\alpha_{t_0} = -180^\circ$

$\theta_{t_0} = -90^\circ$

$a_t = 68.60$ m/sec/sec

From the output (Table 3-V), notice the large missile acceleration required (211.55 m/sec/sec) to intercept a maneuvering target. The trajectories are plotted in Figure (3-16).

G. PROPORTIONAL GUIDANCE (DETAILED ANALYSIS)

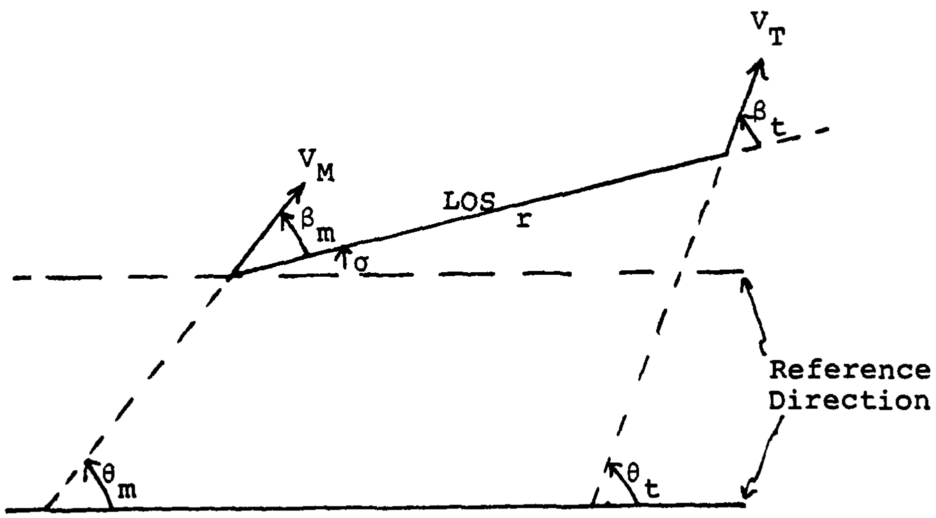


Figure (3-17). Proportional guidance geometry.

Proportional guidance automatically establishes a lead angle and reacts to a changing line-of-sight. The basic guidance law used equates the rate of change of the missile heading to a constant times the rate of change of the line-of-sight. From the above figure this law can be expressed as,

$$\dot{\theta}_m = k\,\dot{\sigma}$$

From the figure, the rate of change of the line-of-sight, $\dot{\sigma}$, is given by,

$$\dot{\sigma} = \frac{V_T \sin \beta_t - V_M \sin \beta_m}{r}$$

As in the case of pursuit and line-of-sight guidance, the parameter of interest here is the normal acceleration; therefore, the missile and target tangential accelerations are assumed to be zero. In this case,

$$a_m = V_M\,\dot{\theta}_m$$

$$a_t = V_T\,\dot{\theta}_t$$

From the guidance law,

$$a_m = V_M\,k\,\dot{\sigma}$$

and

$$a_m r = V_M\,k(V_T \sin \beta_t - V_M \sin \beta_m)$$

Since $\dot{V}_m = \dot{V}_t = 0$, the time derivative of this equation is,

$$\dot{r}\, a_m + r\, \dot{a}_m = k\, V_m\, [(V_t \dot{\beta}_t \cos \beta_t - V_m \dot{\beta}_m \cos \beta_m)] \qquad (1)$$

From the original figure,

$$\theta_m = \beta_m + \sigma$$

$$\dot{\beta}_m = \dot{\theta}_m - \dot{\sigma} = \dot{\theta}_m - \frac{\dot{\theta}_m}{k}$$

$$\dot{\beta}_m = \dot{\theta}_m (1-\frac{1}{k})$$

Also,

$$\dot{\beta}_t = \dot{\theta}_t - \dot{\sigma}$$

$$\dot{\beta}_t = \dot{\theta}_t - \frac{\dot{\theta}_m}{k}$$

Making these substitutions, equation (1) becomes,

$$r\, \dot{a}_m = -a_m\, \dot{r} + k\, V_M\, [\, V_T (\dot{\theta}_t - \frac{\dot{\theta}_m}{k}) \cos\, \beta_t - V_M \dot{\theta}_m (1-\frac{1}{k}) \cos\, \beta_m\,]$$

Since,

$$a_m = V_M\, \dot{\theta}_m$$

$$a_t = V_T\, \dot{\theta}_t$$

$$r\, \dot{a}_m = -a_m\, \dot{r} + k\, V_M\, a_t \cos\, \beta_t - k\, V_M\, a_m \cos\, \beta_m$$

$$- a_m\, (V_T \cos\, \beta_t - V_M \cos\, \beta_m)$$

From Figure (3-17),

$$\dot{r} = V_T \cos \beta_t - V_M \cos \beta_m$$

$$r \dot{a}_m = -2 a_m \dot{r} + k V_M a_t \cos \beta_t - k V_M a_m \cos \beta_m$$

$$\dot{a}_m = \frac{k V_M a_t \cos\beta_t}{r} - \frac{a_m}{r} [2\dot{r} + k V_M \cos\beta_m]$$

Collecting equations;

$$\dot{r} = V_T \cos \beta_t - V_M \cos \beta_m$$

$$\dot{\beta}_t = \dot{\theta}_t - \dot{\sigma}$$

$$\dot{\beta}_m = \dot{\theta}_m - \dot{\sigma}$$

$$\dot{\sigma} = \frac{V_T \sin\beta_t - V_M \sin\beta_m}{r}$$

$$\dot{\theta}_t = \frac{a_t}{V_T}$$

$$\dot{\theta}_m = k \dot{\sigma}$$

The above equations are the equations of motion for a missile using proportional navigation assuming constant missile and target speeds. As with the line-of-sight equations, the motion is quite complex. The equations cannot be solved analytically except for special cases. One such case will be investigated here. That is for a non-maneuvering crossing target.

1. Example IV (Non-Maneuvering Crossing Target)

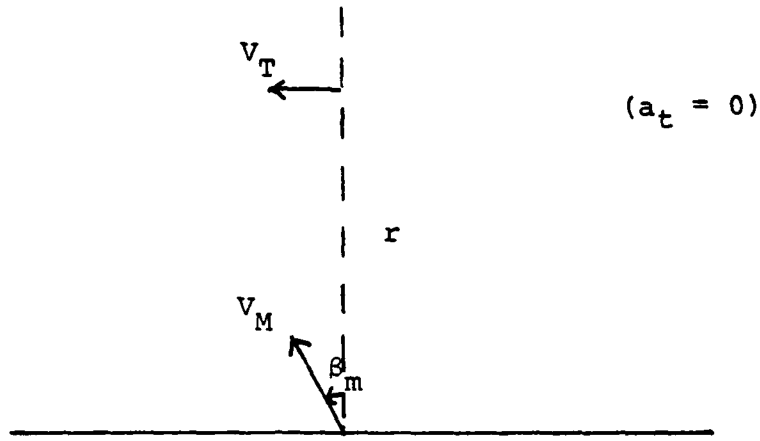


Figure (3-18). Non-maneuvering target.

For this case, $\dot{r} = -V_M \cos \beta_m$ from equation (1)

$$\dot{a}_m = -\frac{a_m}{r} [2\dot{r} - k\dot{r}]$$

$$\frac{\dot{a}_m}{a_m} = \frac{\dot{r}}{r} (k-2)$$

$$\ell n a_m = (k-2)\ell n r + \ell n c_1$$

If $a_m = a_0$ at $r = r_0$

$$a_m = a_0 \left(\frac{r}{r_0}\right)^{k-2}$$

From this equation,

if $k > 2$ $\quad a_m \longrightarrow 0$ as $r \rightarrow 0$

$$\text{if} \quad k = 2 \quad a_m = a_0 = \text{constant}$$

$$\text{if} \quad k < 2 \quad a_m \rightarrow \infty \quad \text{as} \quad r \rightarrow 0$$

From the above example it can be realized that the proportionality constant, k, must be greater than two. A more general analysis of the equations of motion can be obtained by solving the equations numerically. The same Euler's one step method is used here with initial conditions, at t = 0,

$$a_m(0) = a_{m_0}$$

$$r(0) = r_0$$

$$\beta_t(0) = \beta_{t_0}$$

$$\beta_m(0) = \beta_{m_0}$$

$$\sigma(0) = \sigma_0$$

$$\theta_t(0) = \theta_{t_0}$$

$$\theta_m(0) = \theta_{m_0}$$

The algorithm used is as follows:

$$r(i+1) = r(i) + \Delta t \, \dot{r}(i)$$

$$a_m(i+1) = a_m(i) + \Delta t \, \dot{a}_m(i)$$

$$\sigma(i+1) = \sigma(i) + \Delta t \, \dot{\sigma}(i)$$

$$\theta_m(i+1) = \theta_m(i) + \Delta t \, \dot{\theta}_m(i)$$

$$\theta_t(i+1) = \theta_t(i) + \Delta t\ \dot{\theta}_t(i)$$

$$\beta_m(i+1) = \beta_m(i) + \Delta t\ \dot{\beta}_m(i)$$

$$\beta_t(i+1) = \beta_t(i) + \Delta t\ \dot{\beta}_t(i)$$

The trajectory of the missile and target can be determined assuming the missile is at the origin at $t = 0$. From the original figure the missile and target positions are given by,

$$x_m(i+1) = x_m(i) + \Delta t\ V_M \cos \theta_m(i)$$

$$y_m(i+1) = y_m(i) + \Delta t\ V_M \sin \theta_m(i)$$

$$x_t(i+1) = y_t(i) + \Delta t\ V_T \cos \theta_t(i)$$

$$y_t(i+1) = y_t(i) + \Delta t\ V_T \sin \theta_t(i)$$

With initial conditions,

$$x_m(0) = y_m(0) = 0$$

$$x_t(0) = r_0 \cos \sigma_0$$

$$y_t(0) = r_0 \sin \sigma_0$$

Evaluating the missile initial acceleration can be more complicated. One procedure which is both realistic and of interest is to have the missile and target on a constant bearing - decreasing range course ($\dot{a}_t = 0$) when the target initiates a constant g turn at $t = 0$. In this case $a_m(0) = 0$ and the subsequent motion can be found.

TABLE 3-VI

```
10 PRINT "THIS PROGRAM FINDS THE MAXIMUM"
20 PRINT "MISSILE ACCELERATION FOR A"
30 PRINT "PROPORTIONAL NAVIGATION SYSTEM"
35 PRINT
36 DIM X[250],Y[250],U[250],V[250]
38 DIM A[250],T[250],R[250]
40 PRINT "INPUT TIME INCREMENT"
50 INPUT D1
60 PRINT "INPUT NAVIGATION CONSTANT"
70 INPUT K
80 PRINT "INPUT MISSILE VELOCITY"
90 INPUT V1
100 PRINT "INPUT TARGET VELOCITY"
110 INPUT V2
120 PRINT "INPUT TARGET ACCELERATION"
130 INPUT A1
140 PRINT "INPUT INITIAL MISSILE ACCELERATION"
150 INPUT A[1]
160 PRINT "INPUT INITIAL RANGE"
170 INPUT R[1]
180 PRINT "INPUT BETA TARGET"
200 INPUT B1
210 PRINT "INPUT BETA MISSILE"
220 INPUT B2
230 PRINT "INPUT THETA TARGET"
240 INPUT T1
250 PRINT "INPUT THETA MISSILE"
260 INPUT T2
270 PRINT "INPUT SIGMA"
280 INPUT S1
290 I=1
295 PRINT "    MISSILE POSIT                          TARGET POSIT"
296 PRINT
297 PRINT "        X1               Y1                X2                Y2"
300 X[I]=0
310 Y[I]=0
320 U[I]=R[1]*COS(S1)
330 V[I]=R[1]*SIN(S1)
340 PRINT "DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO"
345 INPUT Q1
350 IF Q1=1 THEN 365
360 PRINT X[I],Y[I],U[I],V[I]
365 I=I+1
370 X[I]=X[I-1]+V1*COS(T2)*D1
380 Y[I]=Y[I-1]+V1*D1*SIN(T2)
390 U[I]=U[I-1]+V2*D1*COS(T1)
400 V[I]=V[I-1]+D1*V2*SIN(T1)
410 R2=V2*COS(B1)-V1*COS(B2)
420 A8=K*V1*A1*COS(B1)/R[I-1]
```

```
430 A9=A[I-1]*(2*R2+K*V1*COS(B2))/R[I-1]
440 A3=A8-A9
445 T[I]=(I-1)*D1
450 S2=(V2*SIN(B1)-V1*SIN(B2))/R[I-1]
460 T8=A1/V2
470 T9=K*S2
480 B3=T8-S2
490 B4=T9-S2
500 R[I]=R[I-1]+D1*R2
510 A[I]=A[I-1]+D1*A3
520 S1=S1+D1*S2
530 T1=T1+D1*T8
540 T2=T2+D1*T9
550 B1=B1+D1*B3
560 B2=B2+D1*B4
570 IF A[I]<A[I-1] THEN 600
580 Z1=A[I]
600 IF R[I]>0 THEN 350
601 IF ABS(A[I])<ABS(A[I-1]) THEN 603
602 Z1=A[I-1]
603 Z2=T[I]
618 PRINT
619 PRINT
620 PRINT "MAXIMUM MISSILE ACC IS"Z1" METERS/SEC/SEC"
640 PRINT "MISSILE TIME OF FLIGHT IS  "Z2"  SEC"
700 PRINT "INPUT MINIMUM VALUE OF X"
710 INPUT X6
720 PRINT "INPUT MAXIMUM VALUE OF X"
730 INPUT X7
740 PRINT "INPUT MINIMUM VALUE OF Y"
750 INPUT Y6
760 PRINT "INPUT MAXIMUM VALUE OF Y"
770 INPUT Y7
780 SCALE X6,X7,Y6,Y7
790 PRINT "HAVE THE AXIS BEEN DRAWN, 0=YES,1=NO"
791 INPUT F1
792 IF F1=0 THEN 830
800 XAXIS 0,X7/10
810 YAXIS 0,Y7/10
830 PEN
840 FOR J=1 TO I
850 PLOT X[J],Y[J]
860 NEXT J
870 PEN
880 FOR W=1 TO I
890 PLOT U[W],V[W]
900 NEXT W
910 PEN
1000 STOP
```

The above algorithm was programmed on the HP 9830 computer. The listing is included in Table 3-VI. The inputs and output of the program are the same as the line-of-sight guidance program. Several examples follow which demonstrates the use of the program.

2. Example V (Crossing Maneuvering Target)

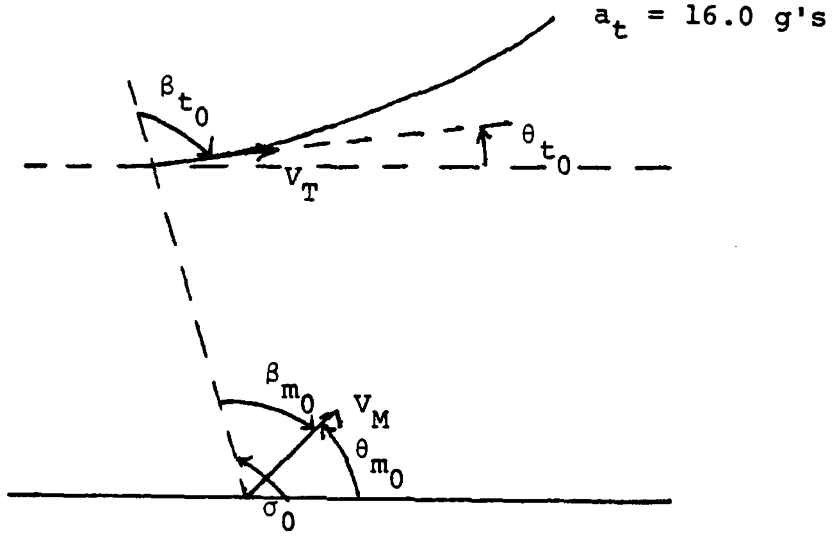


Figure (3-19). Crossing maneuvering target.

V_M = 373 m/sec

V_T = 221 m/sec

a_t = 156.8 m/sec/sec

r_0 = 359 m

θ_{m_0} = 71.57° = 1.2491 rad

θ_{t_0} = 17.57° = 0.3067 rad

β_{t_0} = -91.0° = -1.5882 rad

β_{m_0} = -38.0° = -0.6632 rad

σ_o = 109.57° = 1.9124 rad

The output is listed in Table 3-VII. An important aspect of this problem is the maximum acceleration required (202.92 m/sec/sec).

TABLE 3-VII

THIS PROGRAM FINDS THE MAXIMUM
MISSILE ACCELERATION FOR A
PROPORTIONAL NAVIGATION SYSTEM

INPUT TIME INCREMENT
INPUT NAVIGATION CONSTANT
INPUT MISSILE VELOCITY
INPUT TARGET VELOCITY
INPUT TARGET ACCELERATION
INPUT INITIAL MISSILE ACCELERATION
INPUT INITIAL RANGE
INPUT BETA TARGET
INPUT BETA MISSILE
INPUT THETA TARGET
INPUT THETA MISSILE
INPUT SIGMA

DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO

MISSILE POSIT		TARGET POSIT	
X1	Y1	X2	Y2
0	0	-120.2644734	338.256495
5.896688382	17.69326330	-109.7301208	341.5926479
11.72925942	35.40776626	-99.32072172	345.3003306
17.50036490	53.14238894	-89.04937488	349.3748777
23.21064114	70.89669110	-78.92900524	353.8111620
28.85860473	88.67091421	-68.97234776	358.603601
34.44056825	106.4659749	-59.19193143	363.7461642
39.95057982	124.2834458	-49.60006345	369.2323805
45.38038997	142.1255214	-40.20881377	375.0553462
50.71944940	159.994963	-31.02999988	381.2077340
55.95494106	177.8950225	-22.07517195	387.6818020
61.07184968	195.82934	-13.3555983	394.4694036
66.0530711	213.8018172	-4.882251242	401.5619976
70.87956373	231.8164631	3.334206794	408.9506590
75.53054295	249.8772187	11.2834366	416.6260903
79.98371892	267.9877605	18.95543527	424.578633
84.21557618	286.1512922	26.34054872	432.7982802
88.20169238	304.370331	33.42948387	441.2746885
91.91709127	322.6464989	40.21332036	449.9971918
95.33662288	340.9803284	46.68352174	458.9548139
98.43536132	359.3710956	52.8319462	468.136283
101.1890086	377.8166893	58.65085689	477.5300458
103.5742899	396.3135251	64.13293155	487.1242815
105.5693244	414.8565113	69.27127182	496.906917
107.1539546	433.4390689	74.05941184	506.8656426
108.3100167	452.0532039	78.49132646	516.9879266
109.0215346	470.6896263	82.56143878	527.2610316
109.2748269	489.3379062	86.26462715	537.6720304
109.0585142	507.9866517	89.59623167	548.2078223
108.3634271	526.6236943	92.55206	558.8551496
107.1824200	545.2362632	95.12839268	569.6006142
105.5101054	563.811135	97.32198776	580.4306946
103.3425418	582.3347461	99.13008494	591.3317626
100.6769169	600.7932657	100.550409	602.2901010

TABLE 3-VII (cont)

```
MAXIMUM MISSILE ACC IS 202.9212389    METERS/SEC/SEC
MISSILE TIME OF FLIGHT IS   1.7    SEC
INPUT MINIMUM VALUE OF X
INPUT MAXIMUM VALUE OF X
INPUT MINIMUM VALUE OF Y
INPUT MAXIMUM VALUE OF Y
HAVE THE AXIS BEEN DRAWN, 0=YES,1=NO
```

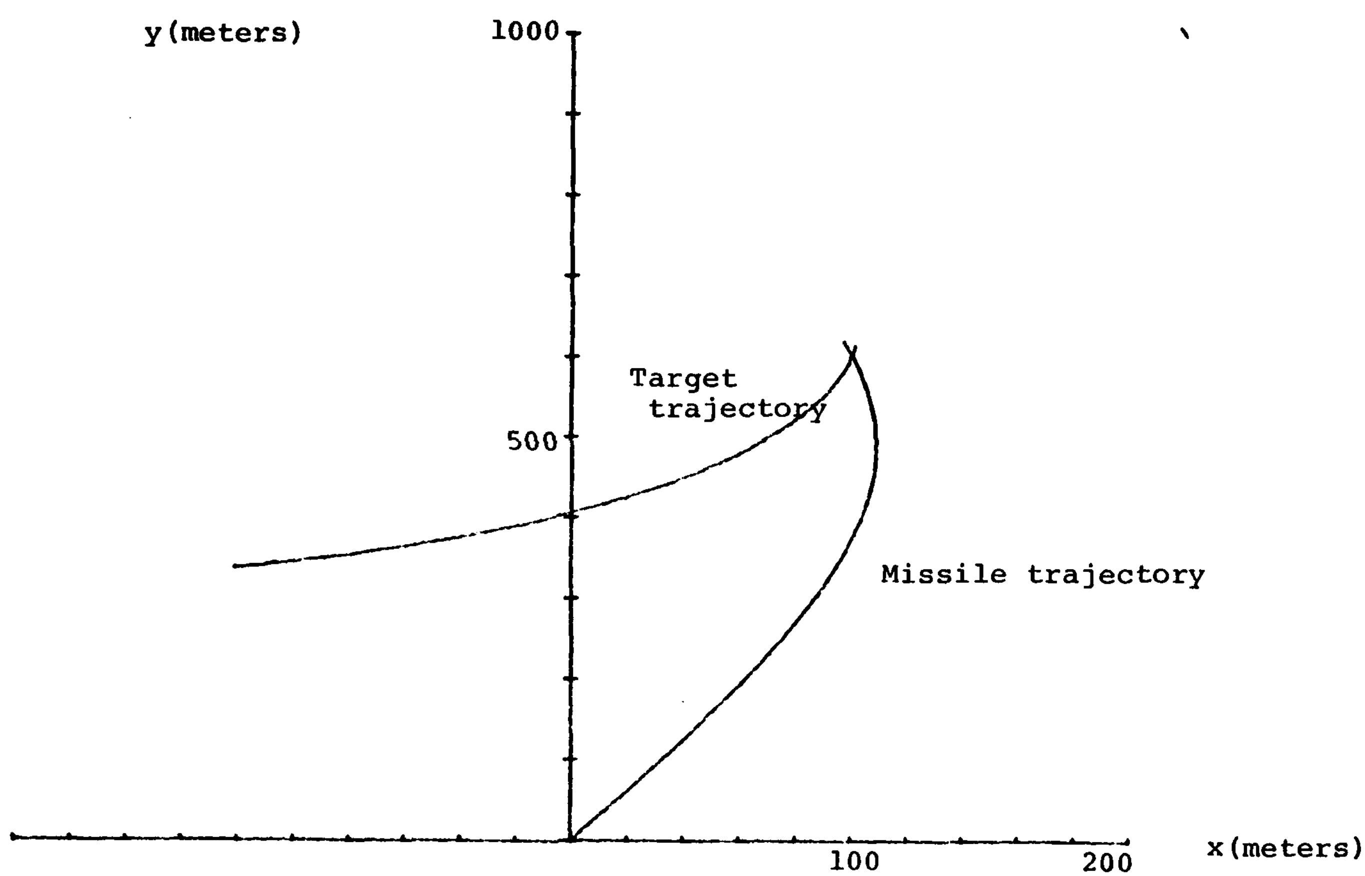


Figure (3-20). Trajectories of crossing, maneuvering intercept.

The same problem was run for line-of-sight guidance with no target acceleration in Example I. The maximum acceleration was 459.25 m/sec/sec. This points out the advantage of proportional navigation over line-of-sight guidance. Figure (3-20) is a plot of the trajectories.

3. Example VI (Effect of k)

This example demonstrates the effect of varying the proportionality constant, k. The scenario is as follows.

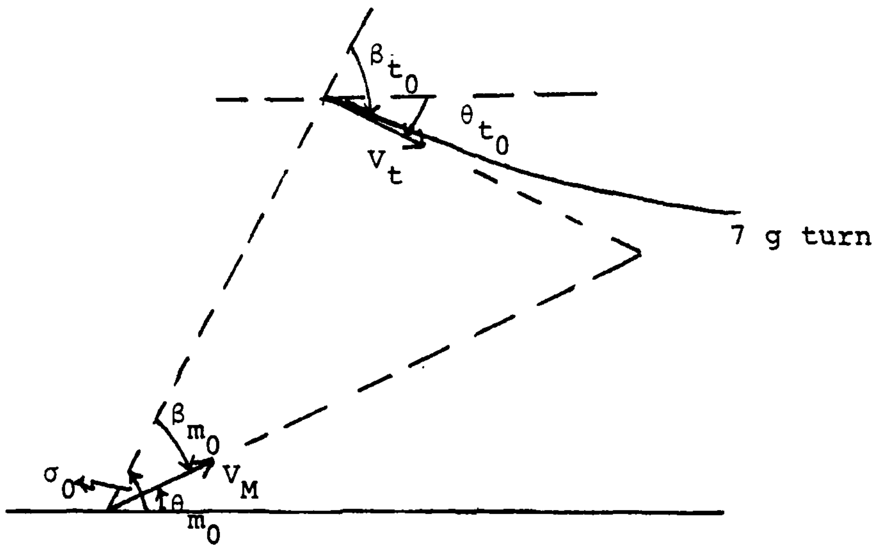


Figure (3-21). Initial geometry.

V_t = 208m/sec

V_m = 413 m/sec

a_t = 68.60 m/sec/sec

β_{t_0} = -106° = -1.85 rad

β_{m_0} = -29° = $-.5061$ rad

TABLE 3-VIII

```
INPUT TIME INCREMENT
INPUT NAVIGATION CONSTANT = 3
INPUT MISSILE VELOCITY
INPUT TARGET VELOCITY
INPUT TARGET ACCELERATION
INPUT INITIAL MISSILE ACCELERATION
INPUT INITIAL RANGE
INPUT BETA TARGET
INPUT BETA MISSILE
INPUT THETA TARGET
INPUT THETA MISSILE
INPUT SIGMA
    MISSILE POSIT                          TARGET POSIT

       X1               Y1               X2               Y2
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO


MAXIMUM MISSILE ACC IS 83.70521471    METERS/SEC/SEC
MISSILE TIME OF FLIGHT IS   3.2    SEC
INPUT MINIMUM VALUE OF X
INPUT MAXIMUM VALUE OF X
INPUT MINIMUM VALUE OF Y
INPUT MAXIMUM VALUE OF Y
HAVE THE AXIS BEEN DRAWN, 0=YES,1=NO


THIS PROGRAM FINDS THE MAXIMUM
MISSILE ACCELERATION FOR A
PROPORTIONAL NAVIGATION SYSTEM

INPUT TIME INCREMENT
INPUT NAVIGATION CONSTANT = 4
INPUT MISSILE VELOCITY
INPUT TARGET VELOCITY
INPUT TARGET ACCELERATION
INPUT INITIAL MISSILE ACCELERATION
INPUT INITIAL RANGE
INPUT BETA TARGET
INPUT BETA MISSILE
INPUT THETA TARGET
INPUT THETA MISSILE
INPUT SIGMA
    MISSILE POSIT                          TARGET POSIT

       X1               Y1               X2               Y2
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO


MAXIMUM MISSILE ACC IS 71.11333197    METERS/SEC/SEC
MISSILE TIME OF FLIGHT IS   3.2    SEC
```

TABLE 3-VIII (cont)

```
THIS PROGRAM FINDS THE MAXIMUM
MISSILE ACCELERATION FOR A
PROPORTIONAL NAVIGATION SYSTEM

INPUT TIME INCREMENT
INPUT NAVIGATION CONSTANT = 5
INPUT MISSILE VELOCITY
INPUT TARGET VELOCITY
INPUT TARGET ACCELERATION
INPUT INITIAL MISSILE ACCELERATION
INPUT INITIAL RANGE
INPUT BETA TARGET
INPUT BETA MISSILE
INPUT THETA TARGET
INPUT THETA MISSILE
INPUT SIGMA
    MISSILE POSIT                          TARGET POSIT

       X1              Y1              X2               Y2
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO


MAXIMUM MISSILE ACC IS 65.38577248    METERS/SEC/SEC
MISSILE TIME OF FLIGHT IS   3.2    SEC
INPUT MINIMUM VALUE OF X
INPUT MAXIMUM VALUE OF X
INPUT MINIMUM VALUE OF Y
INPUT MAXIMUM VALUE OF Y
HAVE THE AXIS BEEN DRAWN, 0=YES,1=NO
```

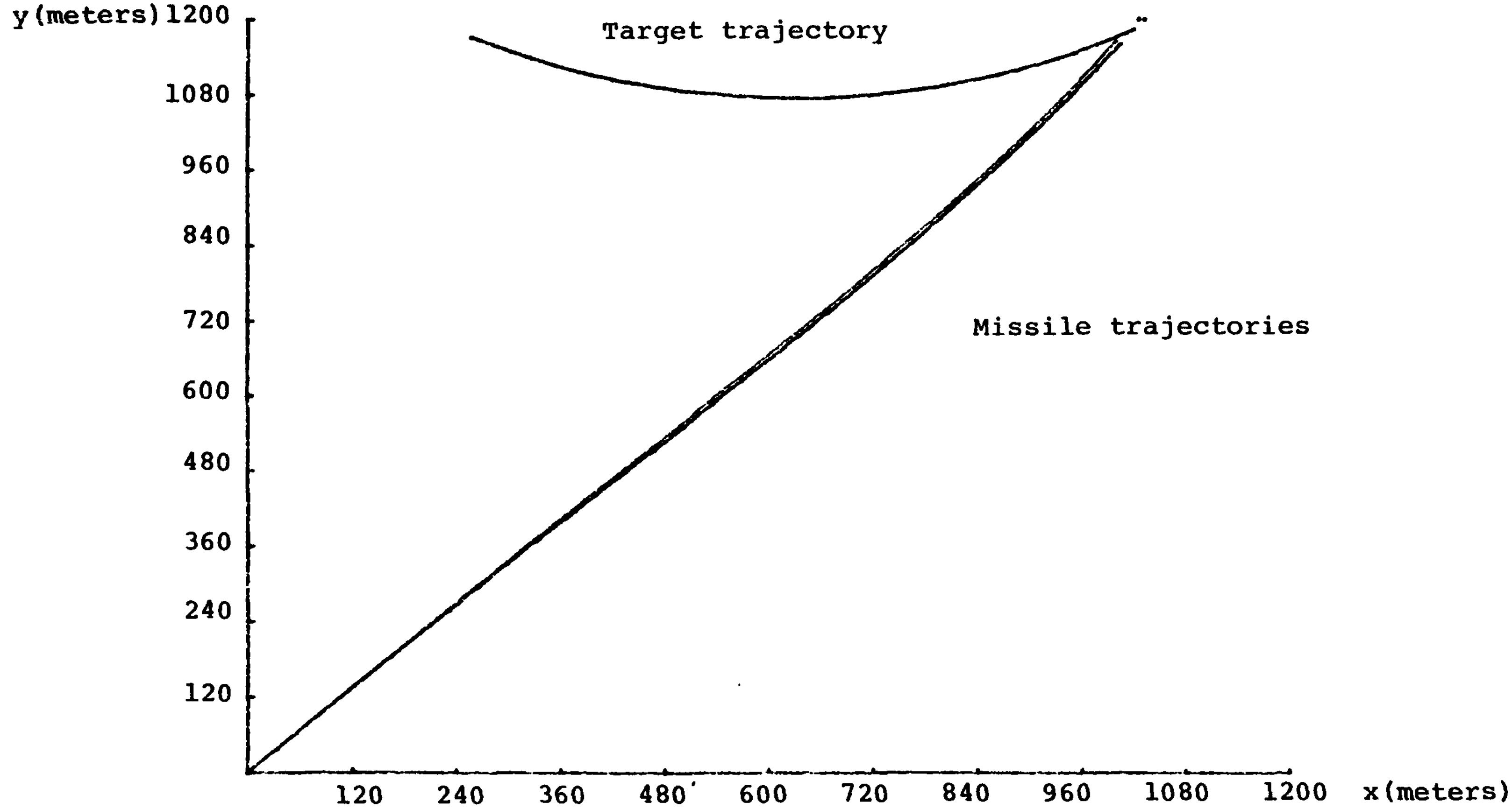


Figure (3-22). Effect of varying k.

$\theta_{m_0} = 48.6^\circ = .8483$ 4ad

$\theta_{t_0} = -28.4^\circ = -.4956$ rad

$\sigma_0 = 77.6^\circ = 1.3544$ rad

The problem was run for k = 3,4, and 5.

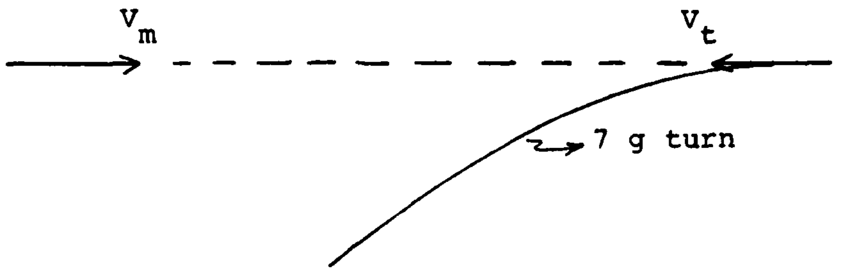
Table 3-VIII is the output. It can be seen that the effect of increasing the proportionality constant is to decrease the maximum acceleration required. Figure (3-22) is a plot of the trajectories.

H. DESIGN EXAMPLE (GUIDANCE LAW SELECTION)

From the examples given in this chapter, it can be seen that a missile designed to encounter a highly maneuverable target, such as a fighter, requires a proportional guidance law to limit the maximum acceleration required of the missile. To select the proportionality constant, it was assumed that the threat could maintain a constant 7g turn at $M_t = 1.5$ and an altitude of 10,000 feet.

Three cases were investigated, (1) A head-on encounter with the target initiating a turn at 10,000 meters range, (2) A crossing encounter in which the target turns into the missile at 10,000 meters range, and (3) An oblique, closing encounter in which the target turns into the missile. The scenario and computer outputs are shown in Figures (3-23), (3-24), and (3-25). From this analysis the crossing encounter requires the largest acceleration (263.2 m/sec/sec).

For the crossing scenario then, the missile speed was varied and the results indicated that as the speed increased the maximum



V_m = 821 m/sec (M = 2.5)

V_t = 492 m/sec (M = 1.5)

r_0 = 10,000 m

θ_{m_0} = 0

θ_{t_0} = 180°

β_{m_0} = 0

β_{t_0} = 180°

σ_0 = 0

k = 4

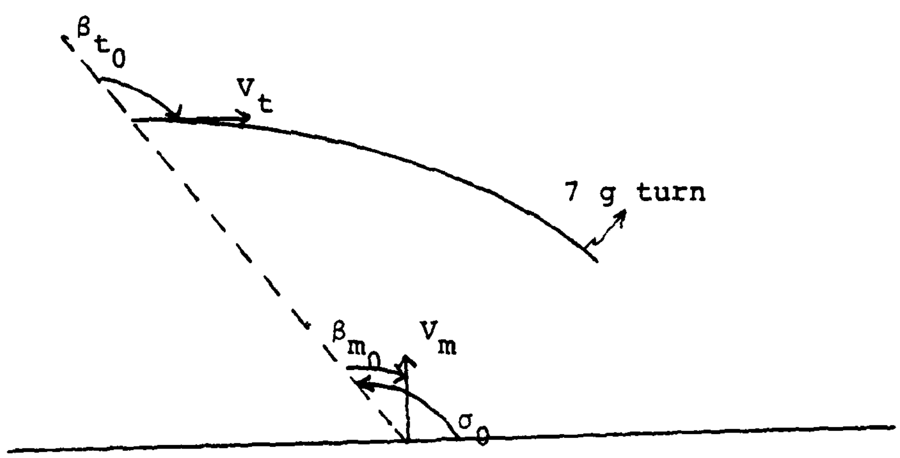
```
THIS PROGRAM FINDS THE MAXIMUM
MISSILE ACCELERATION FOR A
PROPORTIONAL NAVIGATION SYSTEM

INPUT TIME INCREMENT
INPUT NAVIGATION CONSTANT
INPUT MISSILE VELOCITY
INPUT TARGET VELOCITY
INPUT TARGET ACCELERATION
INPUT INITIAL MISSILE ACCELERATION
INPUT INITIAL RANGE
INPUT BETA TARGET
INPUT BETA MISSILE
INPUT THETA TARGET
INPUT THETA MISSILE
INPUT SIGMA
    MISSILE POSIT                        TARGET POSIT

       X1            Y1            X2            Y2
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO


MAXIMUM MISSILE ACC IS 126.1911994    METERS/SEC/SEC
MISSILE TIME OF FLIGHT IS   9      SEC
INPUT MINIMUM VALUE OF X
```

Figure (3-23). Head-on scenario.



$r_0 = 10{,}000$ m

$V_t = 492$ m/sec

$V_m = 821$ m/sec

$\beta_{t_0} = -120^\circ$

$\beta_{m_0} = -46.2^\circ$

$\theta_{t_0} = 0$

$\theta_{m_0} = 73.8^\circ$

$\sigma_0 = 120^\circ$

$k = 4$

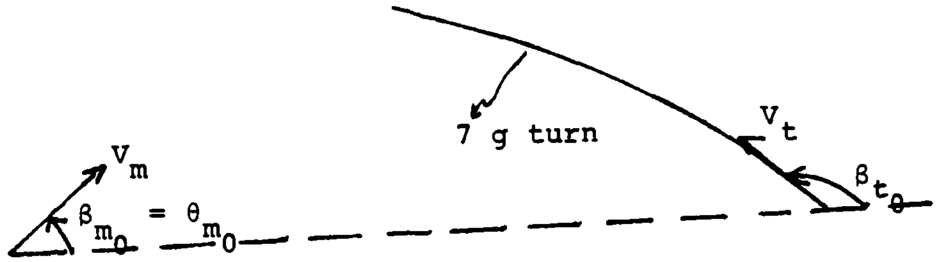
```
THIS PROGRAM FINDS THE MAXIMUM
MISSILE ACCELERATION FOR A
PROPORTIONAL NAVIGATION SYSTEM

INPUT TIME INCREMENT
INPUT NAVIGATION CONSTANT
INPUT MISSILE VELOCITY
INPUT TARGET VELOCITY
INPUT TARGET ACCELERATION
INPUT INITIAL MISSILE ACCELERATION
INPUT INITIAL RANGE
INPUT BETA TARGET
INPUT BETA MISSILE
INPUT THETA TARGET
INPUT THETA MISSILE
INPUT SIGMA
    MISSILE POSIT                      TARGET POSIT

       X1            Y1            X2             Y2
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO


MAXIMUM MISSILE ACC IS 263.1995227    METERS/SEC/SEC
MISSILE TIME OF FLIGHT IS   8.8    SEC
INPUT MINIMUM VALUE OF X
```

Figure (3-24). Crossing scenario.



$V_t = 492$ m/sec

$V_m = 821$ m/sec

$\beta_{t_0} = 135^\circ$

$\beta_{m_0} = 53.9^\circ$

$r_0 = 10{,}000$ m

$\theta_{t_0} = 135^\circ$

$\theta_{m_0} = 53.9^\circ$

$\sigma_0 = 0$

$k = 4$

```
THIS PROGRAM FINDS THE MAXIMUM
MISSILE ACCELERATION FOR A
PROPORTIONAL NAVIGATION SYSTEM

INPUT TIME INCREMENT
INPUT NAVIGATION CONSTANT
INPUT MISSILE VELOCITY
INPUT TARGET VELOCITY
INPUT TARGET ACCELERATION
INPUT INITIAL MISSILE ACCELERATION
INPUT INITIAL RANGE
INPUT BETA TARGET
INPUT BETA MISSILE
INPUT THETA TARGET
INPUT THETA MISSILE
INPUT SIGMA
    MISSILE POSIT                          TARGET POSIT

       X1             Y1              X2              Y2
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO


MAXIMUM MISSILE ACC IS-156.9795962    METERS/SEC/SEC
MISSILE TIME OF FLIGHT IS   8.8    SEC
INPUT MINIMUM VALUE OF X
```

Figure (3-25). Oblique scenario.

TABLE 3-IX

```
INPUT TIME INCREMENT
INPUT NAVIGATION CONSTANT
INPUT MISSILE VELOCITY ——→ M_M = 2.0
INPUT TARGET VELOCITY
INPUT TARGET ACCELERATION
INPUT INITIAL MISSILE ACCELERATION
INPUT INITIAL RANGE
INPUT BETA TARGET
INPUT BETA MISSILE
INPUT THETA TARGET
INPUT THETA MISSILE
INPUT SIGMA
    MISSILE POSIT                          TARGET POSIT

       X1             Y1             X2             Y2
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO


MAXIMUM MISSILE ACC IS 275.5734145    METERS/SEC/SEC
MISSILE TIME OF FLIGHT IS   10.3      SEC
INPUT MINIMUM VALUE OF X


THIS PROGRAM FINDS THE MAXIMUM
MISSILE ACCELERATION FOR A
PROPORTIONAL NAVIGATION SYSTEM

INPUT TIME INCREMENT
INPUT NAVIGATION CONSTANT
INPUT MISSILE VELOCITY ——→ M_M = 3.0
INPUT TARGET VELOCITY
INPUT TARGET ACCELERATION
INPUT INITIAL MISSILE ACCELERATION
INPUT INITIAL RANGE
INPUT BETA TARGET
INPUT BETA MISSILE
INPUT THETA TARGET
INPUT THETA MISSILE
INPUT SIGMA
    MISSILE POSIT                          TARGET POSIT

       X1             Y1             X2             Y2
DO YOU WANT A PRINT OF THE OUTPUT, 0=YES,1=NO


MAXIMUM MISSILE ACC IS 248.233583     METERS/SEC/SEC
MISSILE TIME OF FLIGHT IS   7.8    SEC
INPUT MINIMUM VALUE OF X
```

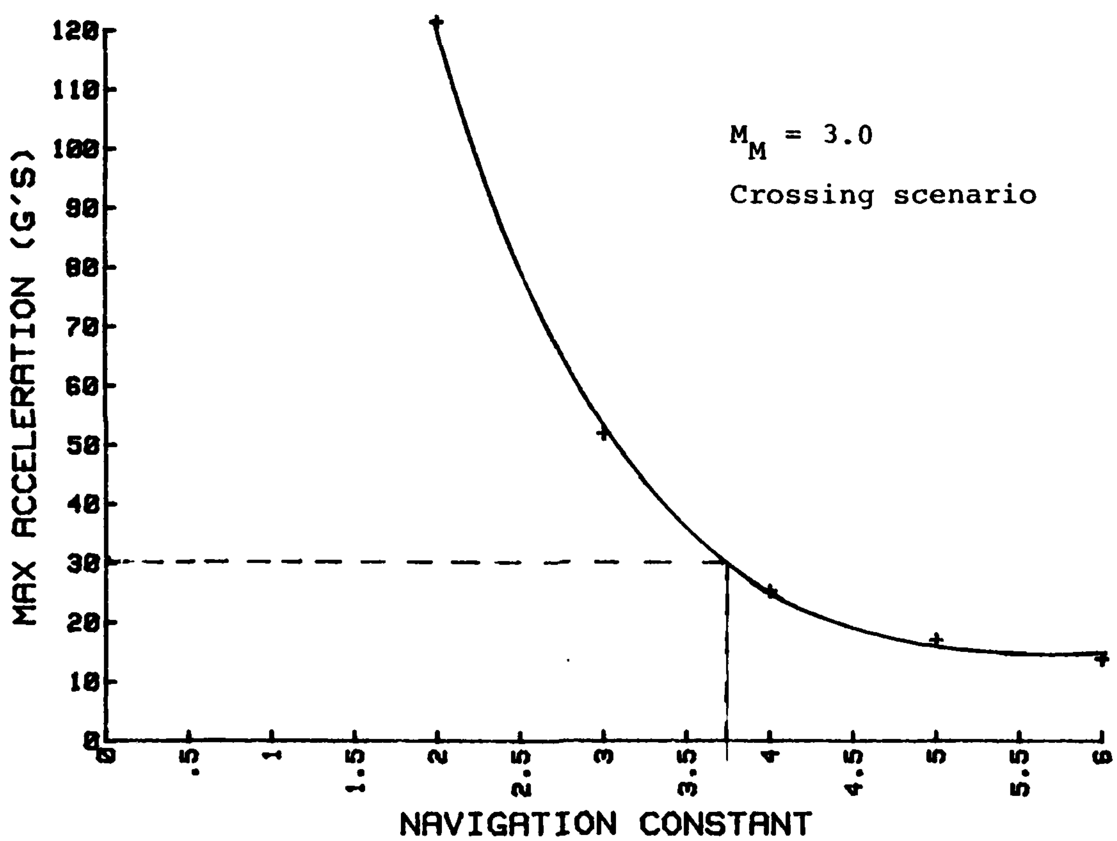


Figure (3-26). Selection of Navigation Constant.

acceleration decreased. The results for $M_M = 2.0$ and $M_M = 3.0$ are shown in Table 3-IX. This result indicates the desirablity of retaining the missile Mach number originally selected.

For the crossing case and a missile speed of $M_M = 3.0$, the proportionality constant was then varied from k = 2 to k = 6. The results are plotted in Figure (3-26). If the maximum acceleration is limited to 31 g's ($3a_t + 10$), the required proportionality constant is $k \cong 3.75$. This is well within the desirable range of 2 - 6 indicated earlier.

From this analysis the required performance objectives are:

$$M_m = 3.0$$

$$k = 3.75$$

$$(a_m)_{max} = 31 \text{ g's}$$

IV. SIZING THE DIAMETER

The missile diameter is determined by one of three driving factors. For relatively short range missiles the diameter will be fixed by either the warhead or the seeker requirements. As might be expected, for longer range missiles the diameter will more likely be fixed by either the warhead or the seeker requirements. As might be expected, for longer range missiles the diameter will more likely be fixed by the propulsion requirements in order to prevent excessive propulsion system lengths. An initial estimate of the missile diameter must be made at this point in order to proceed with the design. The initial seeker requirement can be determined from a knowledge of the lock-on range requirement found in Chapter 2. The warhead necessary to inflict a "kill" can also be estimated from information about the target and characteristic explosives. The propulsion requirement cannot be determined because of the lack of any aerodynamic drag or weight information at this point. For this reason the missile diameter will be now sized for seeker or warhead requirements. The missile propulsion requirements will be determined later in the design process, and it may be necessary at that time to resize the missile to meet these propulsion requirements.

Selection of the type of seeker depends upon the operational arena of the missile. The seeker of a shoulder fired, battlefield missile would not be the optimum seeker of a shipboard missile where antenna and component sizes are not limiting factors. All types of guidance use some portion of the electromagnetic spectrum. The three primary areas of use are the electro-optical, infrared, and radio frequencies. The millimeter wave section of the spectrum is also of current interest in the design of missiles due to small component size and will also be discussed. The following table lists some of the major advantages and disadvantages of the three.

	Advantages	Disadvantages
Optical	Target resolution (detail) Real time information Three dimension effect	Bad weather degrades Night use degrades
Infrared	Improved resolution over RF	Attenuation due to aerosols and atmosphere
RF	Longest range Least absorption and attenuation	Larger components

A. THE RADAR RANGE EQUATION

An omnidirectional antenna is one that radiates power in all directions equally. If the power radiated by an antenna is P_t, the power density at a distance R_t from the source is given by,

$$\text{Power density} = P_t/(4\pi R_t^2)$$

$$4\pi R_t^2 = \text{area of a sphere of radius } R_t$$

Since antennas are normally directive instead of omnidirectional, most of the power is radiated in a particular direction. The gain, G_t, is a measure of the increased power from a directive antenna as compared to an omnidirectional antenna. Therefore the power density from a directive antenna can be expressed as,

$$\text{Power density} = \frac{P_t\ G_t}{4\pi\ R_t^{\ 2}}$$

This is the power density which arrives at the target. The target intercepts a portion of this energy and reradiates it in the opposite direction. The radar cross section, σ, is a measure of the effective area of the target. The power radiated by the target is P_{echo},

$$P_{echo} = \frac{P_t\ G_t\ \sigma}{4\pi\ R_t^{\ 2}}$$

This energy propagates as if it were radiated by an omnidirectional antenna. Therefore if the receiving antenna is a distance, R_r, away the power density at the receiver is

$$(\text{Power density})_r = \frac{P_t\ G_t\ \sigma}{(4\pi\ R_t^{\ 2})(4\pi\ R_r^{\ 2})}$$

If the energy is intercepted by the receiving antenna, which has an effective area as seen by the returned energy of A_r; then the power received by the radar , P_r, is

$$P_r = \frac{P_t\ G_t\ \sigma\ A_r}{(4\pi\ R_t^{\ 2})(4\pi\ R_r^{\ 2})} \tag{1}$$

This is the simplest form of the radar equation and can be used to determine the size of antenna required.

B. ACTIVE RADAR HOMING

Active homing is the method of missile guidance in which the radar transmitter and receiver are located on-board the missile. In this case the same antenna is used for both transmitting and receiving. The radar equation then becomes,

$$P_r = \frac{P_t\ G_t\ \sigma\ A_t}{(4\pi\ R^2)^2}$$

where, $R_t = R_r = R$ and $A_r = A_t$.

The minimum power for which the target can be detected, P_{min}, is a function of many variables. A full development of this term can be found in reference (8).

$$P_{min} = k\ T_0\ B_n\ F_n\ \left(\frac{S_0}{N_0}\right)_{min} \quad .$$

Boltzmans constant is $k = 1.38 \times 10^{-23}$ joule/^{o}k. The value of kT_0 at room temperature is 4×10^{-21} watt/cps of bandwidth. The bandwidth, B_n, noise figure, F_n, and minimum signal to noise ratio, $(S_0/N_0)_{min}$ are all functions of the receiver. Typical

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values are listed below.

$$B_n = 1 \text{ MHz}$$

$$F_n = 7.5 \text{ db} = 2.37 \text{ (for crystal mixer)}$$

$$(S_0/N_0)_{min} = 14.7 \text{ db} = 5.43 \text{ (for probability of detection,}$$
$$P_D = 0.9 \text{ and probability of false alarm,}$$
$$P_{fa} = 1/15 \text{ minutes)}$$

The above values give $P_{min} = 5.15 \times 10^{-14}$ watts. This is the value which will be used throughout this section.

From antenna theory the gain is related to the effective antenna area by,

$$G = \frac{4\pi A}{\lambda^2}$$

The maximum radar range can then be shown to be

$$R_{max} = \left[\frac{P_t \sigma A_t^2}{4\pi \lambda^2 P_{min}} \right]^{1/4} \tag{1}$$

Equation (1) for radar range does not include any system losses. It also does not include the statistical nature of several of the parameters. Because of these assumptions the actual range of a radar may be as small as one-half of what the radar range equation predicts for laboratory conditions. For this reason, twice the required range should be used when using the above equation.

1. Example

The AN/APQ-153 is the airborne attack radar system used on the F-5E aircraft. The following parameters apply to this radar.

$$f_0 = 8\text{-}10 \text{ GHz}$$

$$\lambda = c/f_0 = \frac{3 \times 10^8 \text{ m/sec}}{9 \times 10^9/\text{sec}} = .0333 \text{ m}$$

$$c = \text{speed of electromagnetic propagation}$$
$$= 3 \times 10^8 \text{ m/sec}$$

$$P_t = 80 \text{ kW}$$

$$\text{Antenna} = \text{Parabolic dish } 30.5 \times 40.6 \text{ cm}$$

$$A_t = 0.12383 \text{ m}^2$$

for a target of 1 square meter of radar cross-section,

$$R_{max} = 36.16 \text{ km} = 19.5 \text{ nmiles}$$

For the case of an active homing radar, the size of the transmitting and receiving antenna is the parameter of interest. The antenna size may very well drive the design diameter of the missile. The antenna diameter can be expressed as follows.

$$A_t = \left[\frac{4\pi \lambda^2 P_{min} R_{max}{}^4}{P_t \sigma}\right]^{1/2}$$

Let

$$C = \left[\frac{4\pi \lambda^2 P_{min}}{P_t \sigma}\right]^{1/2} \qquad (2)$$

then

$$A_t = \frac{\pi d_t{}^2}{4} = C R_{max}{}^2$$

$$d_t{}^2 = \frac{4C R_{max}{}^2}{\pi} \qquad \text{therefore,} \quad d_t = 2 R_{max}\sqrt{\frac{C}{\pi}}$$

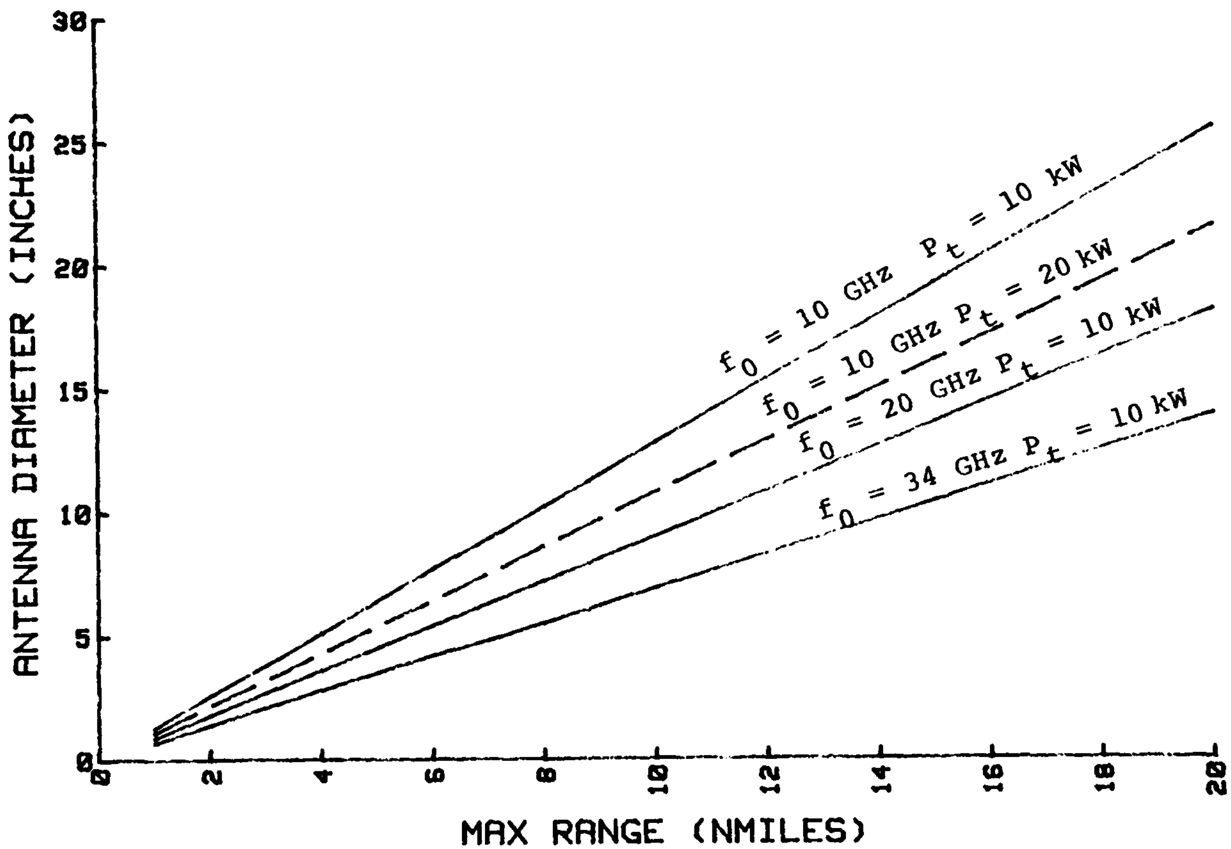


Figure (4-1). Required antenna size.

Equation (2) has been plotted in Figure (4-1) for various values of the transmitter frequency. From this plot and a knowledge of the maximum lock-on range required, the antenna size can be determined.

From equation (2) and Figure (4-1) there are two obvious ways to decrease the antenna size required. (1) Increasing frequency is the best way to reduce antenna and electronic component sizes. The current trend is toward higher frequencies. (Millimeter waves.) One problem is that the equations developed in this section do not include atmospheric attenuation. For frequencies above about 30 GHz the absoprtion due to atmospheric gases increases. This is shown on Figure (4-2). As indicated on this figure there are "windows" where the attenuation is less. These "windows" occur at frequencies of 34 GHz, 94 GHz, 140 GHz, and 220 GHz. These are the frequencies where most of the current research and development is going on. As the frequency increases, the wavelength approaches the size of rain droplets. For this reason, radar performance is greatly reduced in inclement weather. (2) Increasing transmitter power will also decrease the size of antenna necessary. The limiting factor in this area is the lack of high power sources. In the millimeter range the available power from current traveling wave tubes is 50-100 watts. Increasing power is obviously confined to size and weight limitations of missile components.

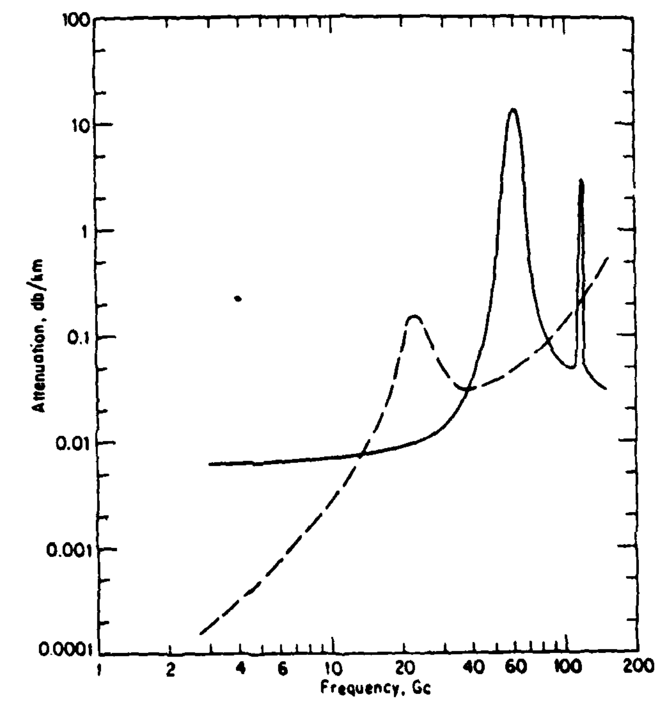


Figure (4-2). Atmospheric Absorption [8].

C. SEMI-ACTIVE HOMING

The advantage of semi-active homing is obvious when the radar range equation is investigated. From equation (1),

$$R_t^{\,2} R_r^{\,2} = \frac{P_t\ G_t\ \sigma\ A_r}{(4\pi)^2 P_{min}}$$

In the above equation the missile range from the target is R_r. The transmitting and receiving antennas are at different ranges and have different characteristics in this case. As before,

$$G_t = \frac{4\pi\ A_t}{\lambda^2}$$

therefore,

$$R_t^{\,2} R_r^{\,2} = \frac{P_t\ A_t\ A_r\ \sigma}{4\pi\ \lambda^2\ P_{min}}$$

The main advantage is in the transmitter characteristics. Since the transmitter is not located in the missile, it is not normally limited in size and weight requirements. In the above equation if a transmitter power and standoff range, R_t, is chosen the receiving antenna can be sized for a maximum homing range, R_{max}, of the missile.

1. Example

$$P_t = 100\ \text{km}$$

$$R_t = 100\ \text{nmiles}$$

$$f_0 = 10\ \text{GHz}$$

$$A_t = 4\ \text{m}^2$$

$$P_{min} = 5.15 \times 10^{-14}\ \text{W}$$

R_{max} (nmiles)	d_r (in)
10	5.8
20	11.6
50	29.1

It can be seen from comparing these numbers to those of Figure (4-1) that the required antenna size is less than one half of that required for an active homing radar of the same frequency.

D. DESIGN EXAMPLE (ANTENNA SIZING)

An active radar was assumed in Chapter 2 to decrease the required missile range. The lock-on range was 10,000 m or 5.4 nmiles. As stated earlier, twice this number should be used for determining antenna size. From Figure (1) for a range of 10.8 nmiles, and a transmitter power of 10 kW at f_0 = 20 GHz, the required antenna size is d = 10 inches.

E. INFRARED SEEKERS

In the design of missile seekers two parameters of primary importance are range and size. The idealized range for an infrared tracker relates these two factors. The idealized range is the range at which the signal-to-noise ratio is unity and is given by,

$$R_0 = \left[\frac{D^* T_a \; T_{IR} \quad D_a^{\;2} \; J}{4 \sqrt{\Delta \; f \; A_d}}\right]^{1/2} \qquad (1)$$

		Typical value
Specific detectivity	D^*	10^{10}
Transmission through atmosphere	T_a	0-1.0
Transmission through IR optics	T_{IR}	0-1.0
Aperture diameter	D_a	
Radiant intensity	J	10^3
Receiver bandwidth	Δf	10^3
Sensitive area of detector	A_d	$10^{-6} - 10^{-1}\ cm^2$

The derivation of equation (1) and its use are the subjects of this section. Some references (9) may give the above equation in terms of the Noise Equivalent Intensity, NEI.

$$R_0 = \left[\frac{J}{NEI}\right]^{1/2}$$

where
$$NEI = \frac{\sqrt{\Delta f\ A_d}}{D^*\ A_a\ T_a\ TIR}$$

1. Planck's Law

The radiant emittance of a body is a measure of the radiant power per unit area emitted from the surface.

$$W = \frac{P}{A}\ \text{watt/cm}^2 \qquad (2)$$

The spectral radiant emittance is the radiant emittance per unit wavelength interval,

$$W_\lambda = \frac{\partial W}{\partial \lambda} \text{ watt/cm}^2\ \mu$$

$$\mu = \text{micron} = 10^{-6} \text{ meters.}$$

Planck's law gives the blackbody spectral radiant emittance as a function of wavelength and temperature,

$$(W_\lambda)_{BB} = \frac{2\ \pi\ h\ c^2}{\lambda^5} \frac{1}{\exp(hc/\lambda kT)-1} \tag{3}$$

h = Planck's constant = 6.6238×10^{-34} Joule-sec

c = speed of light = 3×10^8 m/sec

λ = wavelength

k = Boltzmann's constant = 1.38×10^{-23} Joule/$^\circ$K

T = Absolute temperature, $^\circ$K

Figure (4-3) shows equation (3) for various absolute temperatures. As can be seen the wavelength at which maximum radiant emittance occurs varies with temperature. This maximum occurs at a wavelength given by Wien's displacement law, λ_{max}

$$\lambda_{max}\, T = 2897.8\mu\ ^\circ K$$

2. <u>Emissivity</u>

Actual bodies do not emit radiation according to Planck's law. A more typical plot of radiant emittance is shown in Figure (4-4). Spectral emissivity, ε_λ, is defined as the ratio of the actual spectral radiant emittance to the blackbody spectral radiant emittance,

$$\varepsilon_\lambda = \frac{W_\lambda}{(W_\lambda)_{BB}}$$

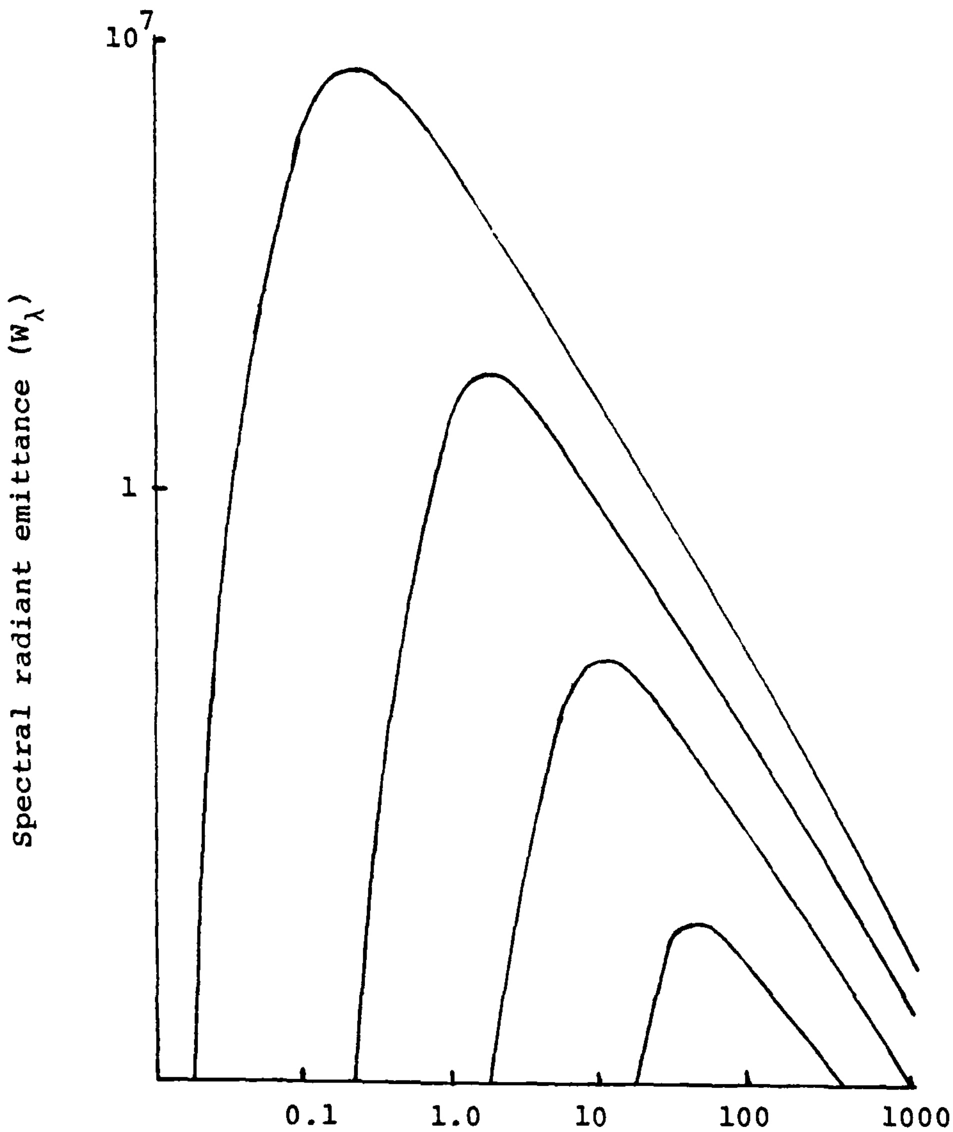


Figure (4-3). Spectral radiant emittance.

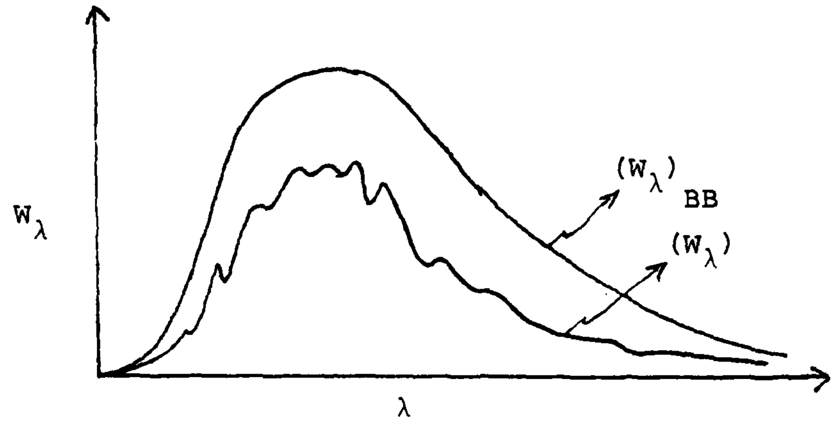


Figure (4-4). Actual spectral radiant emittance.

As shown in the above figure, ε_λ, may vary with wavelength. A grey body is defined as one which has constant spectral emissivity,

$$\varepsilon = \varepsilon_\lambda = \text{constant}$$

IR systems normally use filters to limit the accepted radiation to a specific wavelength band. The radiant emittance of a body between wavelengths λ_1 and λ_2 becomes,

$$W = \int_{\lambda_1}^{\lambda_2} \varepsilon (W_\lambda)_{BB} \, d\lambda$$

In Figure (4-5) the surface at the orgin emits a total energy WA into a hemisphere normal to A.

The radiance is defined as the radiant power per unit solid angle per unit projected area,

$$\text{Radiance} = N = \frac{\partial^2 P}{\cos\theta \, \partial A \, \partial \Omega} = \frac{1}{\cos\theta} \frac{\partial}{\partial \Omega} \quad \frac{\partial P}{\partial A}$$

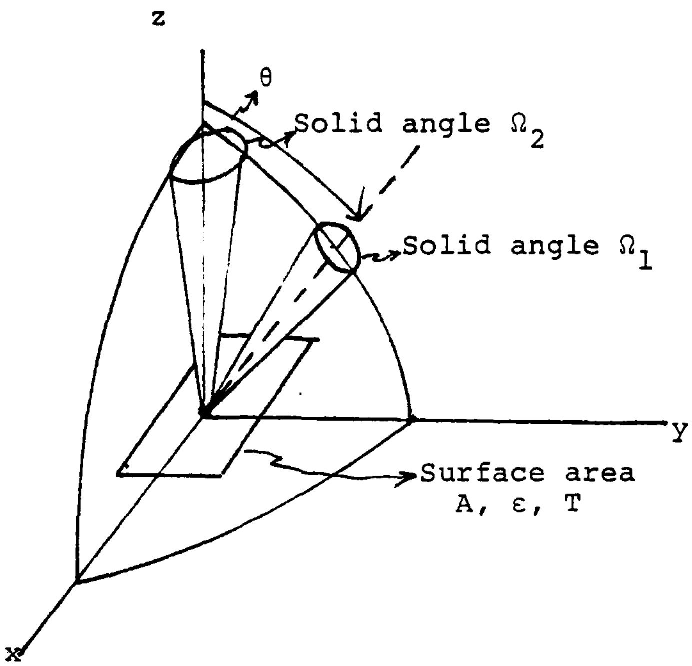


Figure (4-5). Radiant emittance of a body.

From equation (2)

$$N = \frac{1}{\cos\theta} \frac{\partial W}{\partial \Omega} \text{ watts/steradian cm}^2$$

The radiant intensity is defined as the radiant power per unit solid angle from a point source.

$$\text{Radiant intensity} = J = \frac{\partial P}{\partial \Omega} \text{ watt/steradian}$$

The following is a summary of the definitions of radiant energy quantities,

W = radiant emittance, watts/cm^2

J = radiant intensity, watts/steradian

N = radiance, watts/steradian-cm^2

From the definitions the relationship between W, J and N are,

$$W = \pi N = \pi\ J/A$$

From the above definitions and Figure (4-5) the energy into solid angle, Ω_1 is,

$$NA\ \Omega_1 \cos\theta = \frac{W}{\pi}\ \Omega_1\ A \cos\theta$$

The energy into solid angle Ω_2 is given by,

$$NA\Omega_2 = \frac{W}{\pi}\ \Omega_2\ A$$

3. <u>Energy into a Hemisphere</u>

From the definition of radiance and the radiant emittance, the radiance in terms of the radiant emittance can be found,

$$N = \frac{\partial^2 P}{\cos\theta\,\partial A\,\partial\Omega}$$

$$W = \frac{\partial P}{\partial A}$$

$$N = \frac{1}{\cos\theta}\ \frac{\partial W}{\partial\Omega}$$

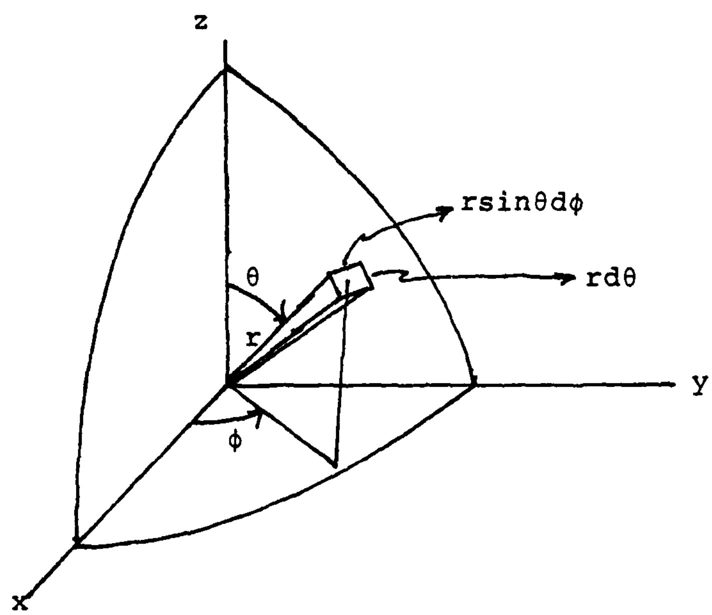


Figure (4-6). Energy emitted into a hemisphere.

From Figure (4-6) the incremental solid angle is

$$d\Omega = \frac{r \sin\theta \, d\phi \, r \, d\theta}{r^2} = \sin\theta \, d\theta \, d\phi$$

If the above surface, A_t, is considered a Lambertian surface, the radiance, N, is independent of the direction of radiation.

$$dW = \cos\theta \, N \, d\Omega$$

$$dW = \cos\theta \, N \sin\theta \, d\theta \, d\phi$$

The total radiant emittance into a hemisphere above the surface is then,

$$W = \int_0^{2\pi} \int_0^{\pi/2} N \cos\theta \sin\theta \, d\theta \, d\phi$$

$$W = 2\pi N \left[\frac{1}{2} \sin^2 \theta\right]_0^{\pi/2}$$

$$W = \pi N$$

4. Targets

Infrared targets include a wide variety of radiation sources. The radiance of most bodies can be divided into that due to self-emission and that due to reflection of incident radiation,

$$N = N_e + N_r$$

The relative magnitude of these contributions depends on a number of factors and varies from target to target and operating environment.

a. Self-emission.

Self-emission, also referred to as thermal emission, depends primarily on the temperature of the body and the emissivity. The most often used appraoch is to consider the body as a grey body which emits radiation according to the Stefan-Boltzmann law.

$$N_e = \frac{\varepsilon \ \sigma \ T^4}{\pi} \text{ watts/steradian-cm}^2$$

where $\sigma = 5.67 \times 10^{-12}$ watts/cm^2($^{\circ}$K)^4

This term is the total radiance (over all wavelengths) and is not the same as used previously.

b. Reflection.

Radiance due to reflectance depends on the illuminating source. This source may be the sun, active, or semi-active sources. It is obvious that at night for a passive infrared system, the radiance due to reflection is not a contributing factor. For this reason only the radiance due to self-emission is considered in this section.

5. Target Temperature

Since the self-emittance of a target depends on the temperature of the target, a method for determining this temperature is needed. The temperature of an aerial target varies depending on the aspect of the target. The propulsion system has hot surfaces such as the nozzle and exhaust plumes. There may also be hot surfaces due to aerodynamic heating and/or solar radiation.

Air breathing engines normally have exhaust plumes ranging from 600 to 1000°K. Rockets typically have much hotter plumes. The flame temperatures for liquid propellants range from 2500 to 7500°K. Solid propellants flame temperatures range from 1700 to 3500°K. The plume temperature can be estimated from the relation.

$$\frac{T_{flame}}{T_{plume}} = \frac{T_0}{T_e} = 1 + \frac{\gamma-1}{2} Me^2$$

where T_0 = stagnation temperature

T_e = static temperature

M_e = Mach number at the nozzle exit

a. Example I

For a flame temperature of 2700°K and an exit Mach number of 3.0 the plume temperature can be found,

$$T_{plume} = \frac{T_{flame}}{1+\frac{\gamma-1}{2} M_e^2} = 1270.6^{\circ}K$$

For many missile encounters the exhaust plume may be shielded from the infrared sensor. For a head-on encounter the temperature of interest is the skin temperature of the target. This temperature is due to aerodynamic heating and is a function of the target speed and the target material. One approach to finding this temperature is through the use of the recovery factor, which requires some knowledge of the material of the target. The recovery factor, r, of a material is defined as follows:

$$r = \frac{T_{surface} - T_{ambient}}{T_{stagnation} - T_{ambient}}$$

The skin temperature of the target then becomes,

$$T_{surface} = T_{ambient} + r\ (T_{stag} - T_{amb})$$

The stagnation temperature is found from the relation,

$$T_{stag} = T_{amb}\ (1 + \frac{\gamma-1}{2} M^2)$$

The Mach number, M, is that of the target and the specific heat ratio, γ, is for air.

b. Example II

A target flying at M = 2.5 where the ambient temperature is 300°K has a recovery factor of 0.75.

$$T_{stag} = 575^{o}K$$

$$T_{surface} = 581^{o}K$$

This is the temperature used, along with the emissivity of the target, to find the radiant emittance of the target from equation (4).

6. Simple IR System

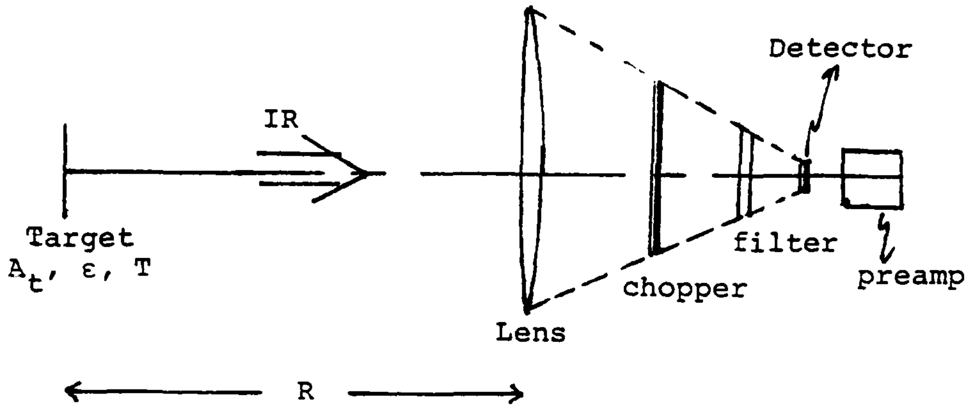


Figure (4-7). Simple IR system.

Figure (4-7), above, shows a simple IR system and a target at a range R. If the system is sensitive to radiation in the 3 to 5 micron region the radiant emittance becomes,

$$W = \int_{\lambda_1=3}^{\lambda_2=5} \varepsilon \; (W_\lambda)_{BB} \; d\lambda$$

$$W = \varepsilon \int_3^5 \left[\frac{2\pi hc^2}{\lambda^5} \; \frac{1}{\exp(hc/\ kT)-1} \right] d\lambda$$

The above integral is best evaluated on the computer. If the ambient temperature and target speed is known, the skin temperature of the target can be determined.

The radiance from the target then becomes,

$$N = \frac{W}{\pi}$$

If Figure (4-7), the solid angle of the aperture as seen from the target is, $\Omega = \frac{A_a}{R^2}$

The power seen at the detector surface is then,

$$\text{IR Power} = N\ \Omega\ A_t$$

The above formula assumes no attenuation by the atmosphere or the IR system optics. This attenuation is significant in actual IR systems. These factors are normally accounted for through the use of atmospheric and IR optics transmission coefficients.

T_a = transmission of the atmosphere

T_{IR} = transmission of the IR optics

The total power at the detector then becomes,

$$P = \frac{T_a\ T_{IR}\ A_t\ A_a\ W}{\pi R^2} \tag{5}$$

7. <u>Detectors</u>

Detectors are devices which are radiation transducers. It's purpose is to change the incoming radiant power to an electrical signal, which can then be amplified. Detectors can be divided into two main categories. (1) Thermal detectors - The responsive element of a thermal detector is sensitive to

temperature changes brought about by the incident radiation.
(2) Photodectectors - Responsive elements of photodetctors are sensitive to the number of incident photons.

Detectors also are made up of windows, apertures and Dewar flasks. The window restricts the bandwidth to which the detector is sensitive. The aperture may limit the field of vie- in order to limit photon noise. The Dewar flask cools the detector which improves the detectivity.

Detectivity of a detector is defined as,

$$D = \frac{\text{signal/noise}}{\text{input power}} = \frac{S/N}{P} \tag{6}$$

The specific detectivity is

$$D^* = D\,[\Delta f\ A_d]^{1/2} \tag{7}$$

Δf = Bandwidth

A_d = Sensitive area of detector

For a tracking system the bandwidth is that of the preamplifier in Figure (4-7). The input to the preamplifier is proportional to the incoming IR energy, which has been modulated to give target resolution from the background and provide line-of-sight information.

A simple chopper is shown in Figure (4-8). It consists of an opaque material which has a wedge cut-out of angle α. The rotation causes the input from a point source to be modulated,

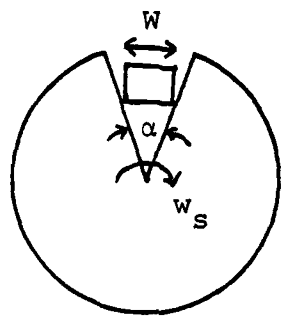


Figure (4-8). Simple Chopper.

while that of the background is not. The input signal to the preamplifier would look like Figure (4-9). The frequency content of the signal in Figure (4-9) can be found from a Fourier Analysis. If the pulses are assumed to be sinusoidal of period T, the optimum bandwidth is,

$$\Delta f = \frac{3}{T}$$

$$T = \frac{W}{\pi \alpha w_s}$$

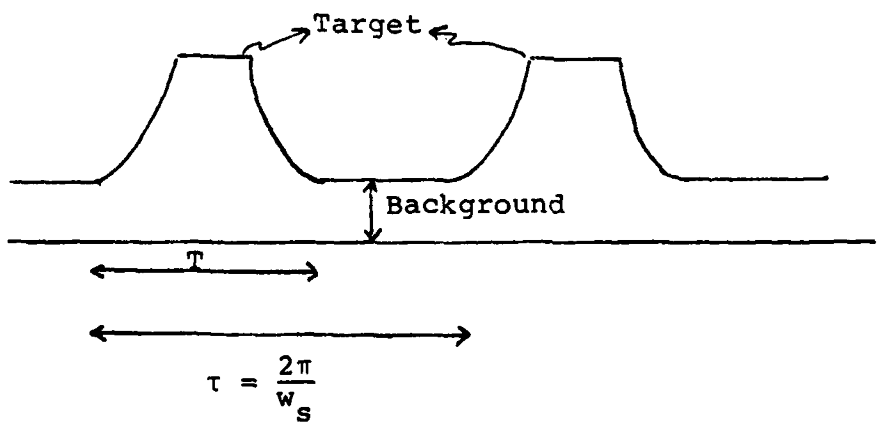


Figure (4-9). Preamp input.

The specific detectivity is characteristic of the detector used. Reference [9] is an excellent source of information on operational detectors.

8. Idealized Range

Equation (5) is,

$$P = \frac{T_a \, T_{IR} \, A_t \, A_a \, W}{\pi R^2}$$

From equations (6) and (7) this becomes,

$$\frac{D^*}{[\Delta f \, A_d]^{1/2}} = \frac{S/N \, \pi \, R^2}{T_a \, T_{IR} \, A_t \, A_a \, W}$$

The idealized range, where the signal to noise ratio is unity, is

$$R_0^{\,2} = \frac{D^* \, T_a \, T_{IR} \, A_t \, A_a \, W}{[\Delta f \, A_d]^{1/2} \pi}$$

To simplify this equation the radiant intensity is given by,

$$J = \frac{A_t \, W}{\pi}$$

Since the parameter of interest in missile design is the aperture diameters A_a, it is replaced with $\frac{\pi D_a^{\,2}}{4}$ so that,

$$R_0 = \left[\frac{D^* \, T_a \, T_{IR} \, \pi \, D_a^{\,2} \, J}{4\sqrt{\Delta f \, A_d}}\right]^{1/2}$$

$$D_a = \left[\frac{R_0^{\,2} \, 4\sqrt{\Delta f \, A_d}}{D^* \, T_a \, T_{IR} \, \pi \, J}\right]^{1/2}$$

a. Example (Idealized Range)

From example II a target flying at M = 2.5 has a skin temperature of 581°K. If this target has a presented area of 1 m^2, the detector size needed to detect the target at a range of 10,000 m can be determined. From Wien's displacement law the maximum radiation occurs at,

$$\lambda_{max} = 4.99\ \mu$$

If the system is designed to accept radiation from 3 to 5 microns, and the emissivity of the target is 0.7.

$$W = \varepsilon \int_3^5 \frac{2\pi hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda kT)-1}\, d\lambda$$

If this equation is integrated on the computer, the radiant emittance becomes,

$$W = 1410 \text{ watts/m}$$

The radiant intensity becomes,

$$J = \frac{A_t\ W}{\pi} = 448.82 \text{ watts}$$

Typical values of the parameters in the idealized range equation are (9)

$T_a = 0.75$

$T_{IR} = 0.95$

$\Delta f = 1000$ cps

$A_d = 1\ cm^2$

$D^* = 1 \times 10^{10}\ (cps)^{1/2}$ cm/watt

Substituting these values into the idealized range equation gives,

$$D_a = 0.0355 \text{ m} = 1.4 \text{ in.}$$

As can be seen the size of the IR seeker is relatively small compared to other seekers. The above analysis is for the "idealized" range. Attenuation of IR radiation can be quite high thereby increasing the seeker size required.

F. WARHEAD SIZING

The conditional kill probability of a missile is the probability that the target is destroyed given that the warhead is delivered to a point in space and the fuze detonates the warhead at a miss distance r.

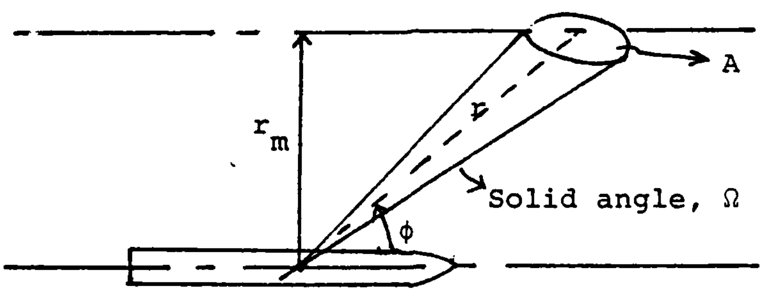


Figure (4-10). Encounter geometry.

The fragment distribution, $D(\phi)$, is the number of fragments per unit solid angle, Ω. The total number of fragments within the cone is,

$$N = D(\phi)\Omega$$

The fragment density, ρ, is the number of fragments per unit of area normal to the path.

$$\rho = \frac{N}{A} = \frac{D(\phi)\Omega}{A}$$

however,

$$\Omega = \frac{A}{r^2}$$

and

$$\rho = \frac{D(\phi)}{r^2} = \frac{D(\phi)\sin^2\phi}{r_m^2} \tag{8}$$

1. Target Vulnerability

The vulnerability of aircraft or missile components is normally determined experimentally. Fragments of a specified size are fired at the component, and the damage is assessed to determine if the fragment would cause a kill. If a large number of fragments are fired, the ratio of killing fragments to hits can be determined. This ratio is defined as the probability that given a hit a kill will result, $P_{K/H} = \frac{N_K}{N_H}$. Assuming the distribution of hits is uniform over the target,

$$P_{K/H} \equiv \frac{A_v}{A_p} \tag{9}$$

A_p = presented area of target

A_v = vulnerable area of target

As would be expected, $P_{K/H}$, depends greatly upon the encounter geometry. It will be dependent upon the aspect of the aircraft, and also depends upon the type of kill specified. If the target is assumed to be a spherical target, the probability of kill given a hit can be assumed constant.

2. Conditional Kill Probability

The fragment density is given by equation (8). From this density expression, the average number of hits, a, on the vulnerable area of the target is,

$$a = \frac{D(\phi)\sin^2\phi}{r_m^2} A_v$$

It is customary to assume that the distribution of hits on the presented area follows a Poisson distribution. The conditional kill probability then becomes,

$$P_D = 1 - e^{-a} \tag{10}$$

$$P_D = 1 - \exp\left[\frac{-D(\phi)\sin^2\phi\ A_v}{r_m^2}\right]$$

The above expression depends upon the fragment distribution, $D(\phi)$. If the warhead casing is scored such that it produces N fragments of uniform size and mass, m, the problem is simplified by formulating an alternate expression for a.

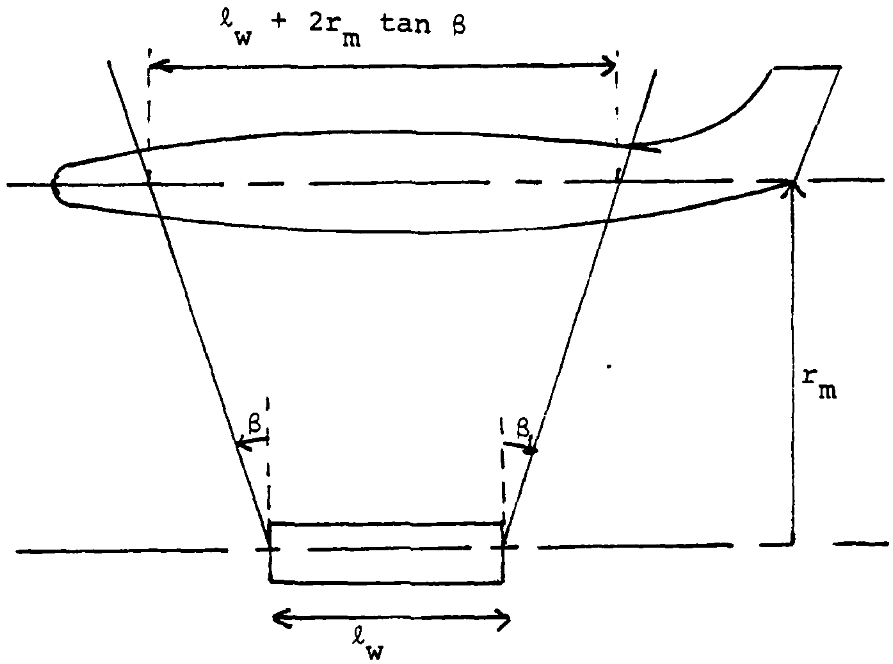


Figure (4-11). Static encounter.

The warhead-target encounter geometry is shown in Figure (4-11). As shown the area of the fragment ring depends on the miss distance, r_m. The area of the ring is given by, A_f.

$$A_f = 2\pi \; r_m(\ell_w + 2r_m \tan \beta)$$

If the N fragments are distributed evenly in A_f, the number of fragments per unit area is

$$\rho = \frac{N}{A_f} = \frac{N}{2\pi \; r_m(\ell_w + 2r_m \tan \beta)}$$

The average number of hits on a vulnerable component is then,

$$a = \rho A_v$$

From equation (9), $A_v = P_{K/H} A_p$

Therefore, $a = \rho P_{K/H} A_p$

$$a = \frac{N P_{K/H} A_p}{2\pi r_m(\ell_w + 2r_m \tan \beta)}$$

If in Figure (4-11), the average target width into the paper is given by $\overline{W}$, the presented area is,

$$A_p = \overline{W}(\ell_w + 2r_m \tan \beta)$$

The average number of hits is then,

$$a_I = \frac{N P_{K/H} \overline{W}}{2\pi r_m} \tag{11}$$

The distance at which the target just fills the fragment ring is the critical miss distance, and the maximum distance for which a_I applies. This is found by setting

$$L = \ell_w + 2r_c \tan \beta$$

From which

$$r_c = \frac{L - \ell_w}{2 \tan \beta}$$

If the miss distance in Figure (4-11) is such that the entire target is always presented to the fragment ring; i.e., $r_m > r_c$, the presented area becomes,

$$A_p = \overline{W} L$$

The average number of hits then becomes, a_{II}

$$a_{II} = \frac{N\ P_{K/H}\ \overline{W}\ L}{2\pi\ r_m(\ell_w + 2r_m \tan \beta)} \tag{12}$$

3. Sizing the Warhead Radius

The parameter of interest in this chapter is the diameter of the warhead required to achieve a specified kill probability. The development thus far is the conditional probability of kill, P_D. It has been assumed that the guidance system delivers the warhead to the point of interest, and the fuze detonates the warhead at this point. Since only the conditional probability of kill is determined, the purpose of this section will be to maximize P_D or to find the warhead diameter which sets $P_D = 1$.

From the threat to be encountered, the target presented area, A_p, and the vulnerability, $P_{K/H}$, can be determined. Also from an alaysis of the threat, the siz e and impact velocity of the fragments necessary to kill the target can be determined. The initial velocity required to obtain the impact velocity is a function of the explosive used and the charge to mass ratio, C/M.

$$\frac{C}{M} = \frac{\text{Mass of explosive/unit length}}{\text{Mass of warhead casing/unit length}}$$

The initial velocity is given by Gurney's equation,

$$V_i = \sqrt{2E}\left[\frac{C/M}{1+C/2M}\right]^{1/2} \tag{13}$$

Gurney's constant, $\sqrt{2E}$, for various explosives are given below [11].

Explosive	Density, kg/m^3	$\sqrt{2E}$, m/sec
TNT	1590	2316.5
RDX	1650	2834.6
HMX	1840	3118.1
PETN	1730	2834.6
Tetryl	1620	2500.0
Composition B	1680	2682.2
Octol	1800	2895.6

From equation (13), the charge to mass ratio necessary to attain the specified initial velocity can be determined.

$$\frac{C}{M} = \frac{V_i^2/2E}{1-V_i^2/2(2E)}$$

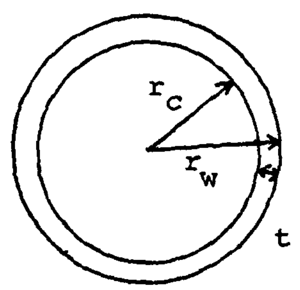


Figure (4-12). Warhead.

From Figure (4-12), C/M can be expressed as,

$$\frac{C}{M} = \frac{\pi r_e^{\;2}\ \rho_e}{(\pi r_w^{\;2} - \pi r_e^{\;2})\rho_c}$$

where

ρ_e = explosive density

ρ_c = casing density

$$\frac{C}{M} = \frac{r_e^{\;2}}{(r_e+t)^2 - r_e^{\;2}} \quad \frac{\rho_e}{\rho_c}$$

$$\frac{C}{M} = \frac{r_e^{\;2}}{2r_e t + t^2} \; \frac{\rho_e}{\rho_c}$$

If $t < < r_e$

$$\frac{C}{M} = \frac{r_e^{\;2}}{2r_e t} \frac{\rho_e}{\rho_c} = \frac{\rho_e}{\rho_c} \frac{r_e}{2t}$$

$$\frac{C}{M} = \frac{\rho_e}{\rho_c} \quad \frac{(r_w - t)}{2t} \tag{14}$$

From equation (14) the casing thickness in terms of the warhead radius can be determined.

$$t = \frac{r_w}{2\,\frac{C}{M}\,\frac{\rho_c}{\rho_e} + 1}$$

With the casing thickness fixed as a function of warhead radius the number of fragments, N, can be determined. In order to achieve the desired velocities of fragments, it is essential to have enough length for the diameter. An acceptable length to diameter ratio for a cylindrical warhead is from two to three. Most air-to-air missiles have a length to diameter ratio of 2.5. For this analysis a value of 2.5 is used.

The warhead casing volume is then given by, V_c,

$$V_c = 2\pi r_w t \ell_w$$

$$V_c = 10\pi t r_w^2$$

The mass of the casing is, m_c,

$$m_c = 10\pi t r_w^2 \rho_c$$

The total number of fragments, N, is obtained by dividing the case mass by the individual fragment mass.

$$N = \frac{m_c}{m} = \frac{10\pi t r_w^2 \rho_c}{m}$$

From the equation (11) or (12) the average number of hits can be determined as a function of warhead radius

$$a_I = \frac{5 t r_w^2 \rho_c P_{K/H} \overline{W}}{m r_m}$$

$$a_{II} = \frac{5 t r_w^2 \rho_c P_{K/H} \overline{W} L}{m r_m (\ell_w + 2 r_m \tan\beta)}$$

The conditional probability of kill can be determined now for a given warhead radius using equation (10).

a. Design Example (Effect of radius on P_D)

If the above equations are programmed for the conditions listed below, a plot of the conditional probability of kill versus warhead radius can be obtained.

Threat: RAM-K

$L = 19.51$ m

$\overline{w} = 6.10$ m

$P_{K/H} = .10$

Fragments:

$m = 105$ grains $= 0.0068$ kg

$V_i = 2133.6$ m/sec

$\rho_c = 7000$ kg/m

$\beta = 20$ degrees

Explosive: Composition B

$\rho_e = 1680$ kg/m

Miss distance: $r_m = 50$ ft $= 15.24$ m

Figure (4-13) is a plot of the output. From this figure it can be seen that a warhead radius of $r_w = .06$ m is required to achieve a conditional kill probability, $P_D = 1.0$. Therefore the missile diameter required for warhead considerations is, d = 4.72 inches.

The warhead radius also varies with the required initial velocity. From the equations for charge to mass ratio

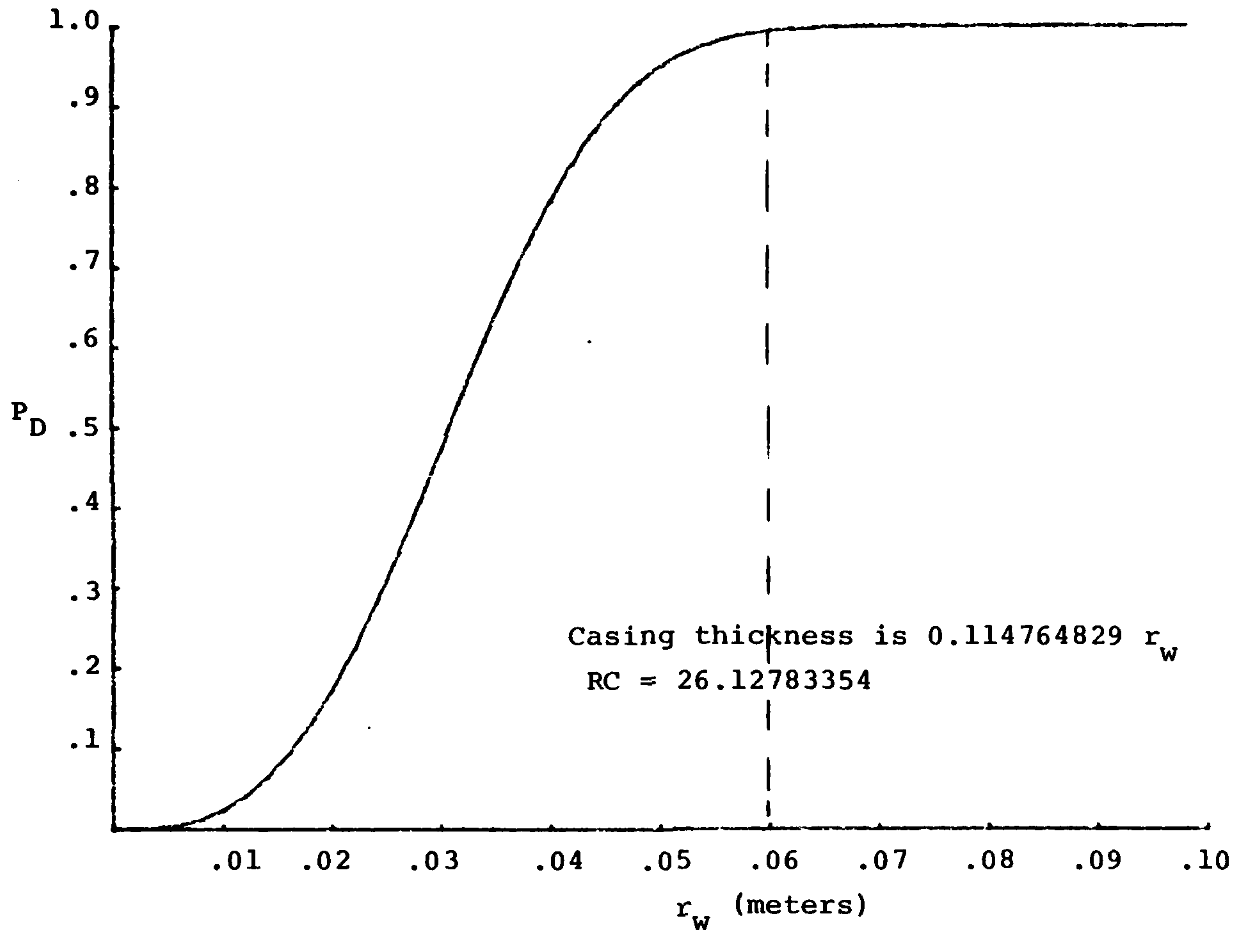


Figure (4-13). P_D versus r_w.

and casing thickness the radius required to achieve a specified kill probability can be determined.

Since,

$$t = \frac{r_w}{2\frac{C}{M}\frac{\rho_c}{\rho_e} + 1}$$

and

$$\frac{C}{M} = \frac{V_i^{\,2}/2E}{1 - V_i^{\,2}/2(2E)}$$

the average number of hits becomes,

$$a_I = \frac{5\rho_c\, P_{K/H}\, \overline{W}\, r_w^{\,3}}{\left[2\left(\frac{V_i^{\,2}/2E}{1 - V_i^{\,2}/2(2E)}\right)\frac{\rho_c}{\rho_e} + 1\right] m r_m}$$

The above equation assumes $r_m < r_c$

Letting

$$b = \frac{5\ {}_c\, P_{K/H}\, \overline{W}}{\left[2\left(\frac{V_i^{\,2}/2E}{1 - V_i^{\,2}/2(2E)}\right)\frac{\rho_c}{\rho_e} + 1\right] m r_m}$$

the probability of kill becomes,

$$P_D = 1 - e^{-br_w^{\,2}} \tag{15}$$

If the conditional probability of kill is selected as $P_D = 0.999$, equation (15) can be solved for the warhead radius.

$$r_w = \left(\frac{6.9078}{b}\right)^{1/3} \qquad (16)$$

The initial velocity, V_i, required to achieve a target kill is a function of the miss distance, fragment size, expected encounter altitude and target characteristics. For this simple analysis the effect of initial velocity on warhead radius will be studied. The effect of varying the initial velocity in equation (16) is plotted in Figure (4-14). The results were determined for various explosives to show their effect on the warhead radius. If an initial velocity of 7000 ft/sec is chosen with Composition B as the explosive the required warhead radius is 2.6 inches.

From this analysis the warhead weight can be found. The casing thickness is given by,

$$t = .115\ r_w \quad \text{(from required C/M)}$$

$$\ell_w = 5\ r_w$$

Therefore, the explosive weight is

$$W_e = \pi(r_w - t)^2 \ell_w\ \rho_e$$

$$W_e = 5.9530\ \text{kg}$$

The casing weight becomes,

$$W_c = (\pi r_w^{\ 2} - \pi r_e^{\ 2})\ell_w\ \rho_c$$

$$W_c = 6.8651\ \text{kg}$$

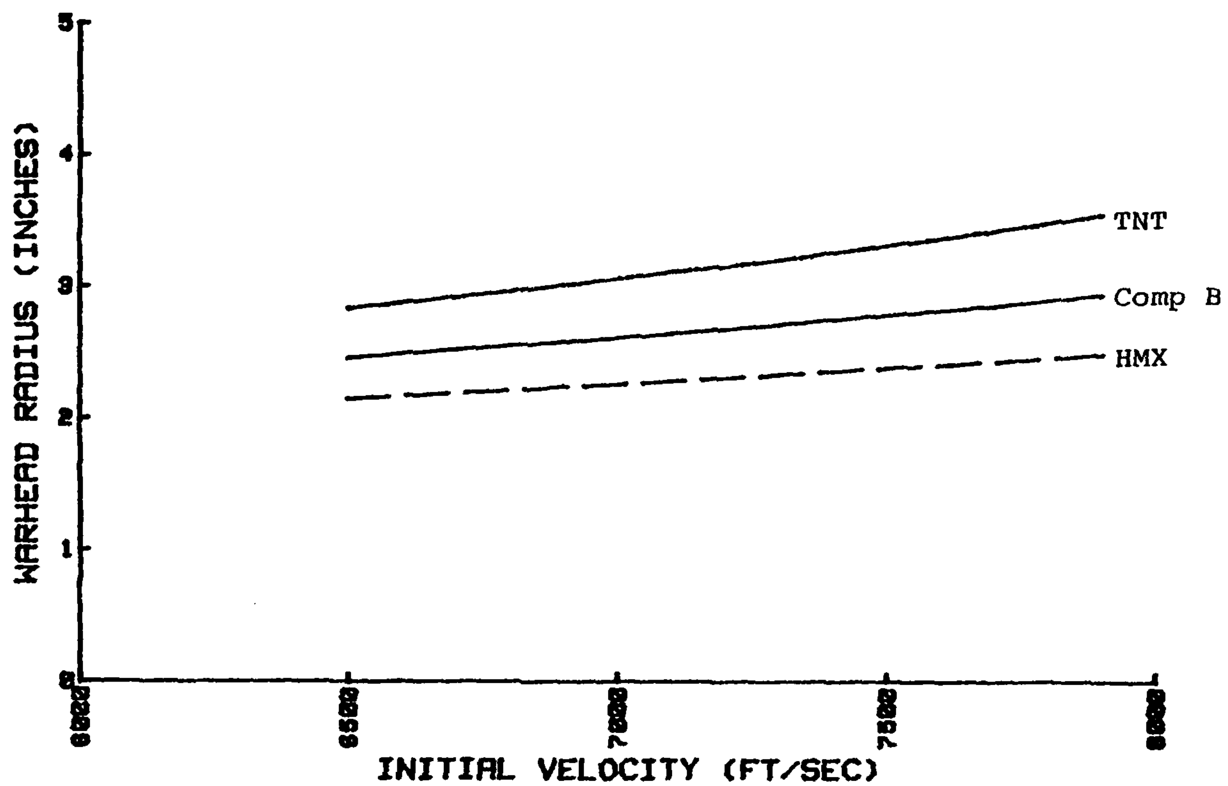


Figure (4-14). Effect of initial velocity on warhead radius.

The total warhead weight becomes,

$$W_{WH} = 12.8181 \text{ kg} = 28.26 \text{ ℓb}$$

The required diameter for the radar antenna was 10 inches and exceeds that required for the warhead. If the warhead is made hollow and kept at the same weight, equation (14) can be reformulated to give

$$\frac{C}{M} = \frac{\left[(r_w - t)^2 - r_i^2\right]\rho_e}{\left[2r_w t - t^2\right]\rho_c}$$

The hollow portion of the warhead is then found from

$$\frac{W_e}{\rho_e} = \pi\left(r_w^2 - r_i^2\right)\ell w$$

Figure (4-15) is the resulting warhead.

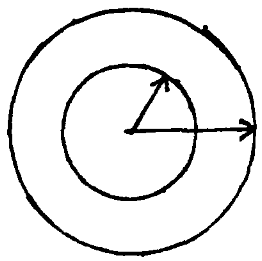
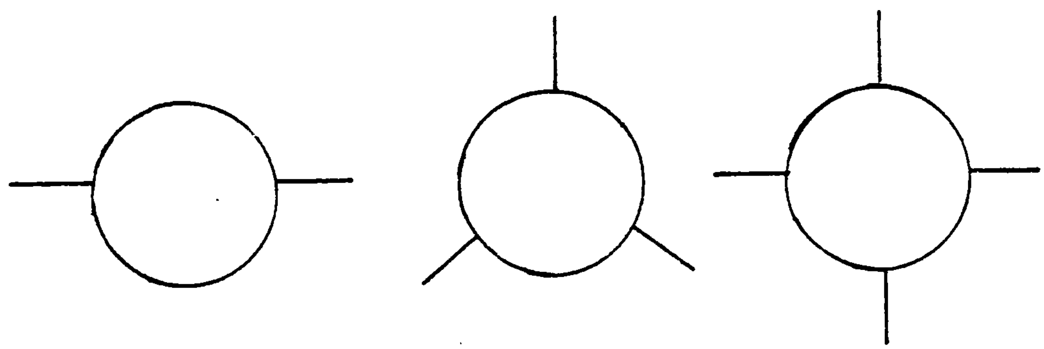


Figure (4-15). Hollow warhead.

V. BASELINE DEFINITION

A. CONTROL CONCEPTS

The lifting and control surfaces of a missile may be of monowing, triwing or cruciform configuration. Figure (5-1) shows these three arrangements.



Monowing Triwing Cruciform

Figure (5-1). Control configurations.

The monowing arrangement is typical of most cruise missiles, which require long range and low drag. For this type of arrangement the missile must bank to orient the lift vector for a maneuver. Because of this, the monowing missile is not as rapid in maneuvering as the cruciform configuration, which can produce lift in any direction instantaneously. The cruciform control also has identical pitch and yaw characteristics which results in a simpler control system. The triwing configuration is used very seldom for conventional missiles. It can be shown that the triwing missile requires larger wing size; therefore, there is little drag savings even though there is one less wing than with the cruciform missile [10]. From this discussion it can be seen why the cruciform configuration is the most commonly used for tactical missiles of short or medium range.

The positions of the lifting surfaces on the missile body depends on the method of control used for the missile. There are three conventional methods of control for tactical missiles. These are; 1) Wing control; 2) Tail control; 3) Canard control.

1. Wing Control

Wing control missiles normally have large movable wings located slightly behind the missile center of gravity. Because of the small moment arm the wing surface must be relatively large to provide control effectiveness. As would be expected, larger activators are required for moving the wings. A positive deflection of the wings causes a positive normal force; therefore, the missile reacts almost instantaneously; thus making wing control the fastest reacting method of control. Because of the smaller moment arm, the resulting smaller pitching moment and instantaneous lift result in smaller angles of attack. This feature makes wing control missiles attractive for applications where theincidence angle must be kept small. Air breathing applications often use wing control because of inlet performance degradation at higher angles of attack. This type of control is also good for fixed seekers.

2. Canard Control

Canard control is normally the method of control where the movable surfaces are placed as far forward as possible. Because of the resulting larger moment arm, smaller surfaces are required to provide control effectiveness. Lift on the missile is still developed primarily by the aft (wing) lifting surface. Response is slower than wing control because of the need to pitch the missile to an angle of attack before lift is developed. Higher angles of attack are needed to generate the required lift. One advantage of this type of control is convenience of packaging. Since the controls and avionics are forward of the propulsion system, the need for connectors is elminated. For stability reasons the wing of a canard control missile must be located farther aft than a conventional wing-tail configuration. The zero lift drag is normally lower than wing control missiles due to smaller surfaces.

3. Tail Control

Like the case of canard control, a tail control missile has the movable surface as far from the center of gravity as possible. This also results in a larger moment arm and therefore smaller surface required. Control deflection is the opposite of that for canard or wing control since a negative control deflection results in a pitching moment that pitches the nose up and therefore a positive lift on the main lifting surface (wing). Tail control is normally the slowest method of control. One advantage is that the flight controls are at the end of the missile requiring the propulsion system to be located forward of other types of control. This results in less center of gravity movement as the propellant grain burns. This becomes a definite advantage for longer range missiles.

B. GROSS WEIGHT AND CENTER OF GRAVITY

Since the component weights and their precise locations cannot be determined at this point in the design process, some method of estimating the total weight and center of gravity is needed. There are two approaches commonly used to find the gross weight of missiles in the conceptual design phase. One is through the use of the historical data discussed in Chapter 2. Since the warhead weight is known, an estimate of the gross weight is now,

$$W_G = \left(\frac{W_G}{W_{WH}}\right)_{AVG} W_{WH}$$

Another method, which is used extensively in the design of aircraft, is the use of regression formulas to find gross weight or component weights in terms of parameters that are known early in the design. Reference (7) has derived such a formula for the gross weight of a missile. It is,

$$W_G = K_G (L)^{2.13} (D)^{1.14} \tag{1}$$

K_G = Constant to be determined

L = Total missile length (inches)

D = Missile diameter (inches)

The constant K_G in equation (1) is derived from a baseline (generic) missile. In this case

$$K_G = \frac{(W_G)_{baseline}}{(L)^{2.13}_{baseline} \quad (D)^{1.14}_{baseline}}$$

The accuracy of a regression formula such as equation (1) depends upon how close the synthesized missile is to the baseline for which K_G was determined. If the parameters used vary more than 20 percent, the accuracy of the regression equation decreases rapidly; therefore, if the parameters length and diameter vary significantly from those of the baseline, equation (1) may give an erroneous estimate of the gross weight. As an aid in determining the gross weight, the following values of K_G were derived from data given in reference [7].

Missile	Figure	K_G
SRAAM	(5-2)	.00128
MRAAM	(5-3)	.00118
LRAAM	(5-4)	.00093
SAM	(5-5)	.00108

Figures (5-2), (5-3), (5-4), and (5-5) show the generic missiles from which these values were derived.

The center of gravity of the baseline missile for this section is taken to be 60 percent of the total length. At this point sufficient information has been developed to define the baseline missile from which design iterations will be made. The lifting

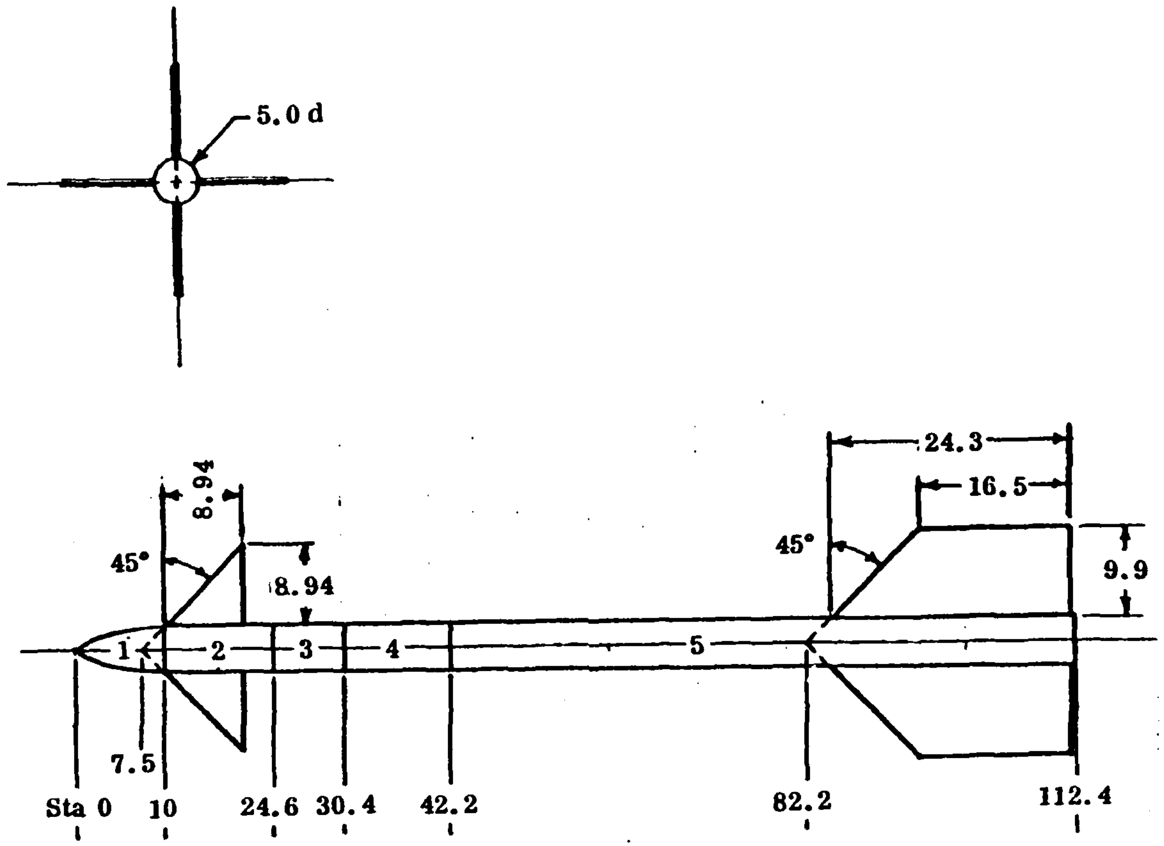


Figure (5-2). Generic SRAAM configuration [7].

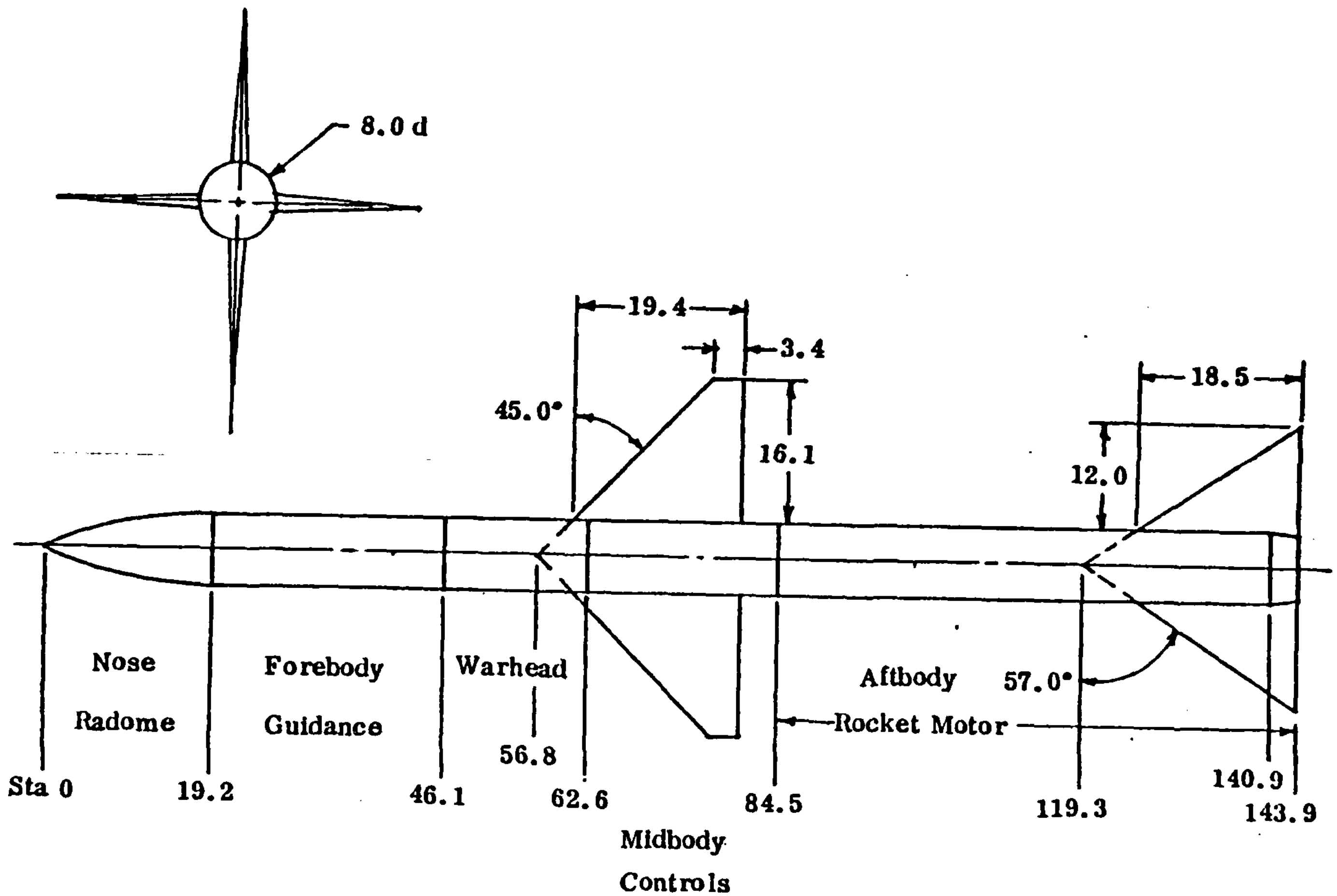


Figure (5-3). Generic MRAAM configuration [7].

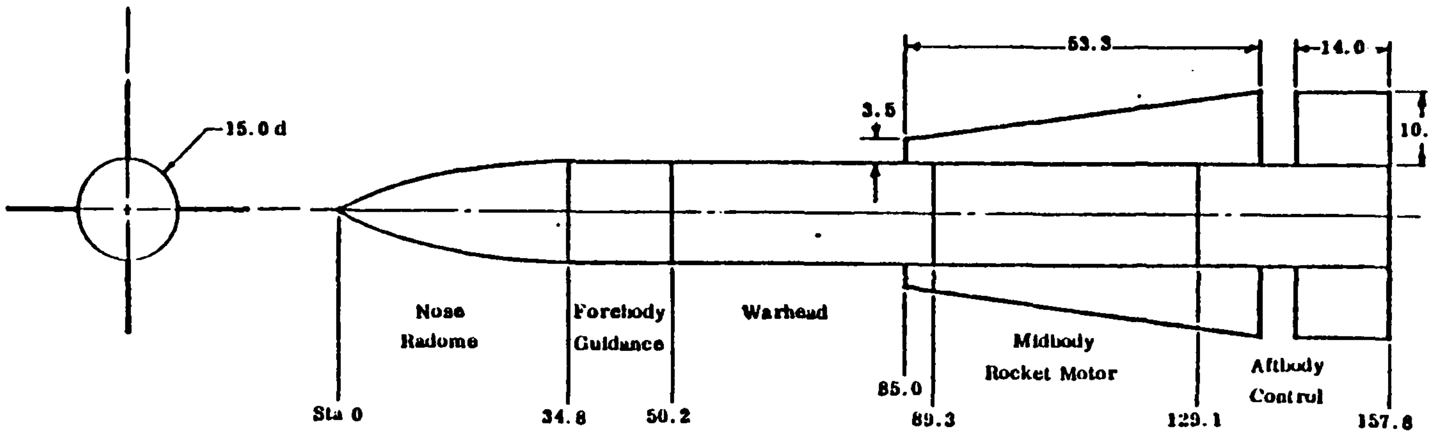


Figure (5-4). Generic LRAAM configuration [7].

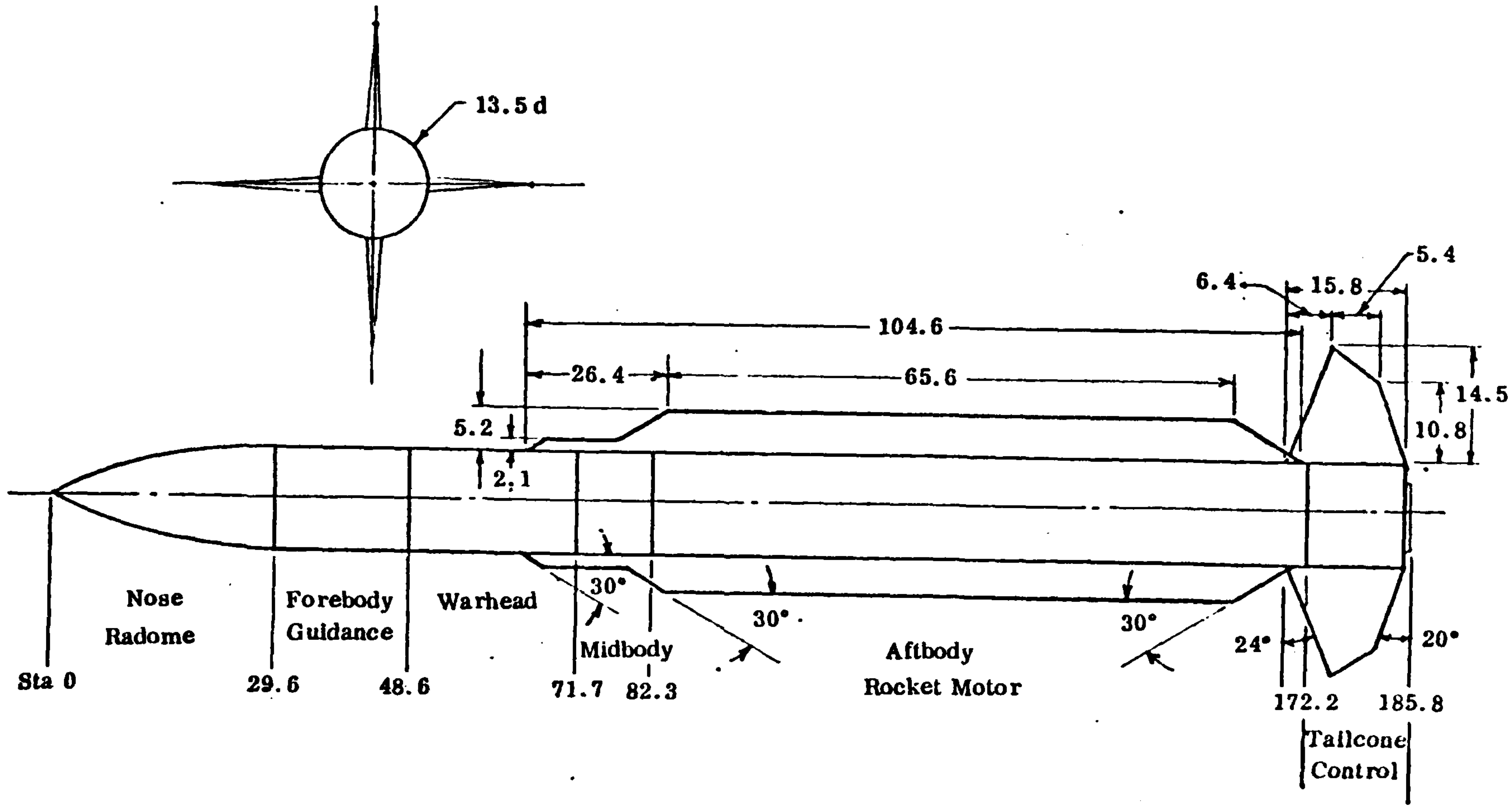


Figure (5-5). Generic SAM configuration [7].

surface planform for the baseline is taken as a delta planform. As will be shown later, this wing planform will be very close to an optimum wing.

C. DESIGN EXAMPLE (BASELINE DEFINITION)

The threat for which this missile is designed is a highly maneuverable fighter. For this threat a canard control, cruciform configuration is chosen. The rationale is that this configuration will provide the fast response necessary at minimum drag. The diameter was fixed at 10 inches due to antenna considerations in Chapter 3. From historical data in Chapter 2,

$$L = \left(\frac{L}{D}\right) D = (15.89)\ 10 = 158.9 \text{ inches}$$

$$L_N = \left(\frac{L_N}{D}\right) D = 22.3 \text{ inches}$$

The MRAAM of Figure (5-3) is used as a generic missile for selecting K_G. Inserting length and diameter into equation (1), the first estimate of gross weight becomes,

$$W_G = .00118\ (158.9)^{2.13}\ (10)^{1.14} = 794.83 \text{ lb}$$

The total lifting surface required is then, from historical average,

$$S = \left(\frac{S}{W}\right)_{AVG} (W_G) = \left(\frac{1}{88.09}\right)(794.83)$$

$$S = 9.02 \text{ ft}^2$$

Since the canard to wing area ratio is known from historical data,

$$S_c/S_W = 0.20$$

$$S_W = 7.52 \text{ ft}^2$$

$$S_c = S - S_W = 1.50 \text{ ft}^2$$

Lifting surfaces (delta planform). From historical data,

$AR_W = 1.61$

$AR_c = 3.74$

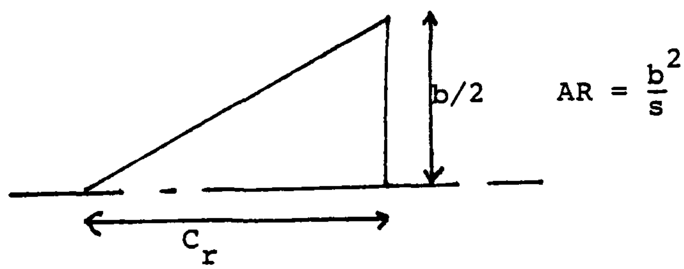


Figure (5-6). Lifting surface.

Wing: $(b)_W = \sqrt{AR_W \; S_W} = 3.48 \text{ ft}$

$$(C_r)_W = 2\; S_W/b = 4.32 \text{ ft}$$

Canard:

$$(b)_c = \sqrt{AR_c \; S_c} = 2.37 \text{ ft.}$$

$$(C_r)_c = 1.27 \text{ ft.}$$

The baseline missile is now defined. The canards are placed as far forward as possible. The wings are placed as far aft as possible to ensure the center of pressure is behind the center of gravity. The exact location of the wings will be modified in the next chapter. Figure (5-7) is a drawing of the baseline missile.

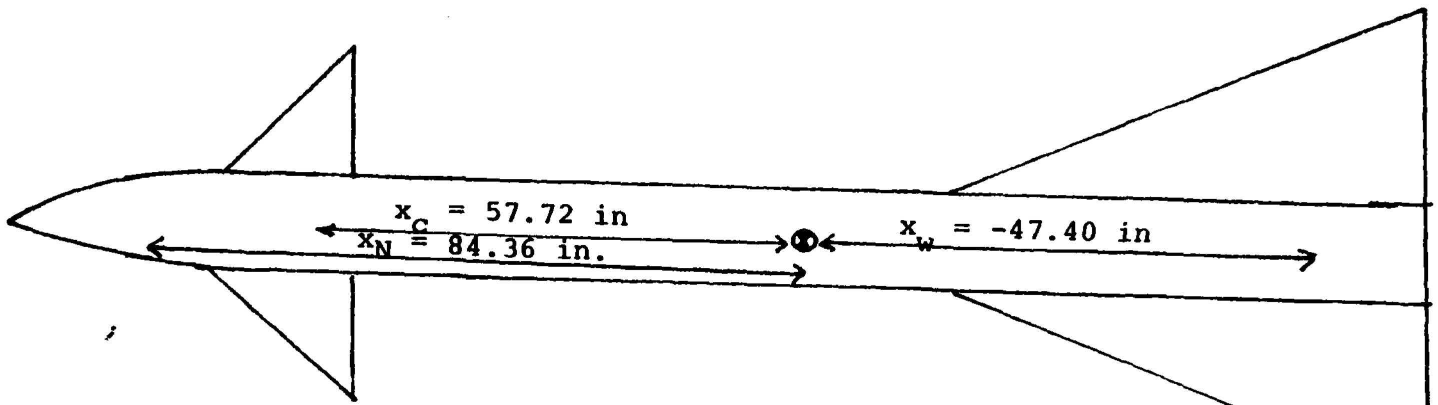


Figure (5-7). Baseline missile.

VI. LINEAR AERODYNAMICS

The total drag on the missile is used to size the propulsion needed for the cruise segment of flight. The wing size depends upon the maximum lift required by the missile. The wing and tail are normally placed to provide minimum drag during cruise or a certain stability margin at launch. To make any of the above calculations, values of the aerodynamic coefficients are needed. This chapter presents the background aerodynamic theory necessary for these initial calculations. The theory used is linear aerodynamic theory and slender body theory, from which simple calculations can be made. Where linear theory did not apply, an attempt was made to find existing empirical expresions, which yield results accurate enough for initial calculations. The full nonlinear theory will be presented in Chapter 9. The reference area for all coefficients in this report is the missile maximum cross sectional area. The reference length is the maximum missile diameter.

A. MISSILE DRAG

The total drag of a missile consists of zero lift drag, C_{D_0}, and induced drag, C_{D_i} .

$$C_D = C_{D_0} + C_{D_i} \tag{1}$$

The zero lift drag can be found from a component build up method in which the contributions due to the nose, body and lifting surfaces are added together to obtain the total zero lift drag.

Care must be taken to reference the appropriate areas when using this method. The total is then multiplied by 1.25 to account for interference effects and variations in skin roughness [12].

$$C_{D_0} = 1.25 \left[(C_{D_0})_N + (C_{D_0})_B + (C_{D_0})_W + (C_{D_0})_T \right] \qquad (2)$$

The method used to find the components drag depends upon the speed regime in which the missile is operating. Since this report is concerned primarily with supersonic tactical missiles, supersonic zero lift drag will be discussed here. The component supersonic zero lift drag can be divided into skin friction, C_{D_f}, and wave drag, C_{D_W}.

$$(C_{D_0})_W = (C_{D_f})_W + (C_{D_W})_W$$

1. <u>Supersonic Skin Friction</u>

The flow over a body traveling at supersonic speeds is likely to be turbulent; so the incompressible skin friction coefficient is given by,

$$C_{f_i} = \frac{.455}{(\log_{10} R_e)^{2.58}} \qquad (3)$$

The Reynolds number in equation (3) is based upon the cruise altitude and speed and upon the characteristic length for the component being determined. The Reynolds number is given by.

$$R_e = \frac{\rho V_M x}{\mu}$$

where $x = L_N$, the length of the nose

L_{CB}, the length of the body without the nose

$(\bar{c})$, the mean aerodynamic chord

The compressibility correction to equation (3) is,

$$C_f = C_{f_i} (1 + 0.15 M_M^2)^{-0.58} \tag{4}$$

From equation (4) the skin friction drag coefficient for each component can be found when referenced to the appropriate area.

$$(C_{D_f})_N = (C_f)_N \frac{(S_{wetted})_N}{S_{ref}}$$

$$(C_{D_f})_B = (C_f)_B \frac{(S_{wetted})_B}{S_{ref}}$$

The lifting surface skin friction drag is determined in a similar manner. Care must be taken to include all surfaces in the wetted area calculation for the lifting surfaces.

2. Supersonic Wave Drag

The supersonic wave drag consists of components contributed by the nose and lifting surface. Nose wave drag depends on the shape of the nose, and the most common nose shapes are conical, ogival and hemispherical. Reference [10] lists empirical formulas for finding the form(wave) drag of various nose shapes at zero angle of attack.

(1) Conical; $C_{D_W} = (0.083 + 0.097/M_M{}^2)(\sigma/10)^{1.69}$

$$\sigma = \tan \frac{D}{2L_N} = \text{Nose semi-vertex angle (Degs)}$$

The center of pressure for a conical nose is at the centroid of the nose planform or two thirds the length of the nose.

(2) Ogival; $C_{D_W} = P \left\{ 1 - \dfrac{2[196(L_N/D)^2 - 16]}{28(M + 18)(L_N/D)^2} \right\}$

$$P = (C_{D_W}) \text{ for conical nose}$$

The center of pressure for an ogive noise is,

$$\frac{C_P}{L_N} = \frac{1}{2}\left[\frac{50(M + 18) + 7M^2P\ (5M - 18)}{40(M + 18) + 7M^2P\ (4M - 3)}\right]$$

The semi-vertix angle for an ogive is twice the equivalent cone angle.

(3) Hemispherical; The drag on a hemispherical nose is extremely high compared to other nose shapes, and is difficult to estimate. An initial estimate of the wave drag can be found from Figure (6-1).

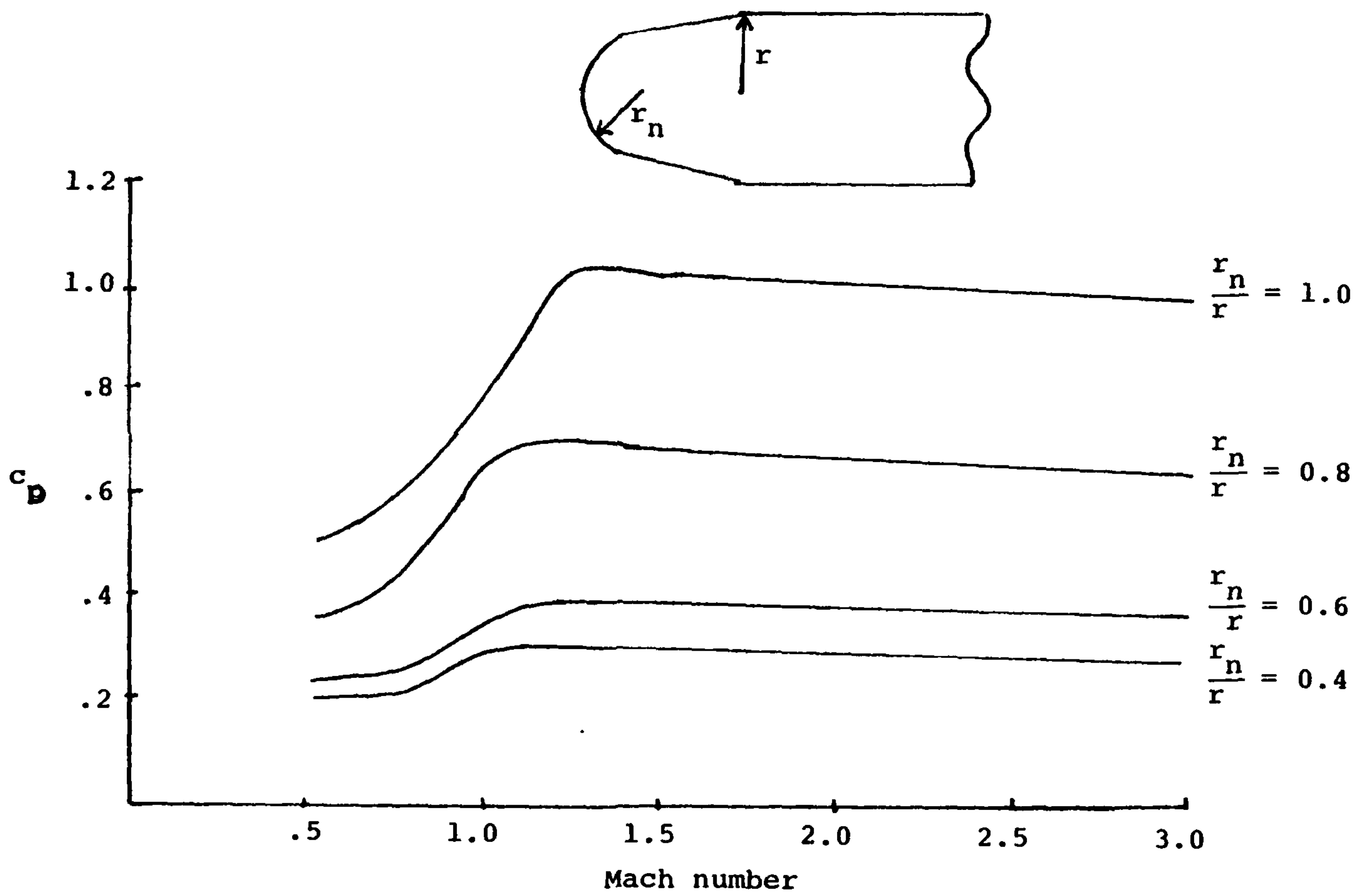


Figure (6-1). Hemispherical nose wave drag.

The wave drag due to the lifting surfaces can be found using the methods of reference [12]. For a double wedge airfoil with sharp leading edges as shown in Figure (6-2), the wave drag is given by the following formulas:

(1) Supersonic leading edge,

$$C_{D_W} = \frac{B}{\beta} \left(\frac{t}{c}\right)^2 \frac{S_W}{S_{ref}}$$

(2) Subsonic leading edge,

$$C_{D_W} = B \cot \Delta_{LE} \left(\frac{t}{c}\right)^2 \frac{S_W}{S_{ref}}$$

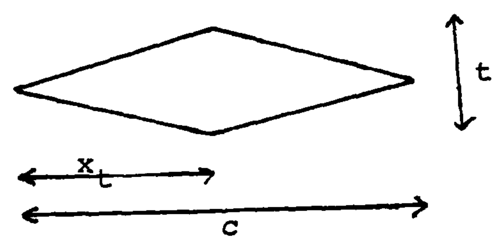


Figure (6-2). Double wedge wing [12].

where $B = \dfrac{c/x_t}{1 - x_t/c}$ Δ_{LE} = leading edge sweep

$\beta = \sqrt{M^2 - 1}$ S_W = planform area

3. <u>Base Pressure Drag</u>

The drag contribution of the blunt base for non-boattailed bodies is given in reference [4] as,

$$C'_{AB} = -C_{P_B} = -\frac{2}{\gamma_{M_M}{}^2}\left\{\left(\frac{2}{\gamma+1}\right)^{1.14}\left(\frac{1}{M_M}\right)^{2.8}\left[\frac{2\gamma M_M - (\;\, -1)}{\gamma+1}\right] -1\right\}$$

This term assumes no jet thrust from the base of the missile, or that the missile is operating in the power off condition. This term is not included in equation (2), which is not a bad assumption for powered flight where the nozzle exit area is approximately equal to the base area of the missile. For the case where the nozzle exit area is much less than the base area as in Figure (3), the base pressure contribution should be included.

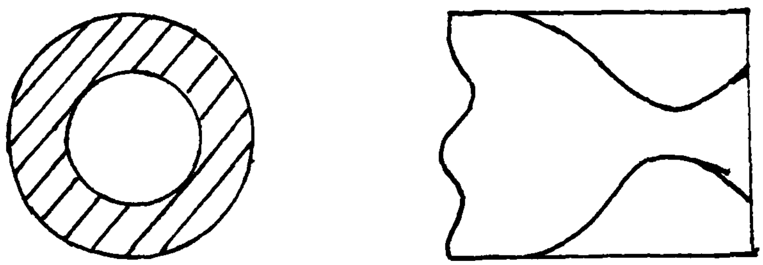


Figure (6-3). Base pressure areas [10].

In this case the base drag is,

$$C_{AB} = C_{AB}' \frac{S_b}{S_{ref}}$$

S_b = shaded area of Figure (6-3)

4. Induced Drag

The induced drag on a missile is the drag due to lift. This drag is caused by the component of the lift vector in the drag direction. For supersonic flow the induced drag is given by,

$$C_{D_i} = \frac{1}{C_{N\alpha}} C_L^{\,2}$$

where;

$$C_L = \frac{W}{q\, S_{ref}}$$

The lift curve slope, $C_{N\alpha}$, will be developed later in this chapter.

B. DESIGN EXAMPLE (ZERO-LIFT DRAG CALCULATION)

The thickness to chord ratio of the wing and tail have not yet been determined; however, it is desirable to construct the lifting surface as thin as structurally possible to minimize the wave drag. Since structures have not been covered the minimum thickness to chord ratio is estimated at 3 percent. The flight and geometric conditions determined thus far are;

$h = 10{,}000$ ft

$M_M = 3.0$

$S_{ref} = 0.5454$

$(t/c)_W = (t/c)_C = 0.03$

$S_W = 7.52$ ft

$S_C = 1.50$ ft

$L_N = 1.8583$

$L_{CB} = 11.3833$

$(\bar{c})_W = 2.8816$

$(\bar{c})_C = 0.8467$

From these conditions the following table can be constructed.

	Nose	Afterbody	Wings	Canards
x	1.8583	11.3833	2.8816	0.8467
S_{wetted}	3.3394	29.8014	15.0400	3.0000
R_e	2.984	18.282	4.6280	1.360
C_{fi}	0.0025	0.0020	0.0024	0.0029
C_f	0.0015	0.0012	0.0015	0.0017
C_{D_f}	0.0095	0.0652	0.0827	0.0187
C_{D_W}	0.1545	----	0.0400	0.0050
C_{D_0}	0.1640	0.0652	0.1227	0.0237

The zero lift drag for the wings and canards in the above table take into account that there are two sets of wings (4 panels). The total missile zero lift drag then becomes,

$$C_{D_0} = 1.25 \left[(C_{D_0})_N + (C_{D_0})_{AB} + (C_{D_0})_W + (C_{D_0})_C \right]$$

$$C_{D_0} = 0.4695$$

C. MISSILE LIFT CURVE SLOPE

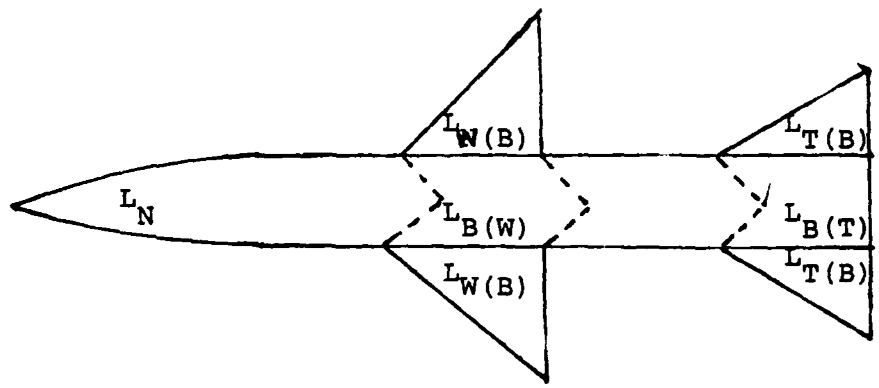


Figure (6-4). Wing-body-tail lift [13].

For the purposes of this section lift on a wing-body-tail combination can be taken as the sum of the components in Figure (6-4). These consist of,

L_N = lift on the nose

$L_{W_{(B)}}$ = lift on the wing in the presence of the body

$L_{B_{(W)}}$ = additional lift on the body due to the presence of the wing

$L_{T_{(B)}}$ = lift on the tail in the presence of the body

$L_{B_{(T)}}$ = additional lift on the body due to the presence of the tail

The lift of only the wing-body combination can be defined as, L_C, where,

$$L_C = K_C L_W \tag{5}$$

The lift of the wing alone, L_W, is that obtained from thin airfoil theory or experiment considering the exposed area only. The constant K_C in equation (5) is defined as

$$K_C \equiv K_{B(W)} + K_{W(B)}$$

From this equation, $K_{B(W)}$ is the ratio of the additional body lift in the presence of the wing to the wing alone lift for zero control deflection, $\delta = 0$.

$$K_{B(W)} = \frac{L_{B(W)}}{L_W} = \frac{(C_{L\alpha})_{B(W)}}{(C_{L\alpha})_W} , \qquad \delta = 0$$

$$K_{W(B)} = \frac{L_{W(B)}}{L_W} = \frac{(C_{L\alpha})_{W(B)}}{(C_{L\alpha})_W} \qquad \delta = 0$$

The interference factors, $K_{B(W)}$ and $K_{W(B)}$ have been determined from slender body theory for wing-body combinations. Figure (6-5) is a plot of these values. The wing alone lift curve slope, $(C_{L\alpha})_W$ is determined from thin airfoil theory or experiment. The lift curve slope of delta wings with supersonic leading edges is given by,

$$C_{L\alpha} = \frac{4}{\beta} \quad \text{where} \quad \beta = \sqrt{M_M{}^2 - 1} \qquad k < \varepsilon$$

For subsonic leading edges this becomes.

$$C_{L\alpha} = \frac{2\pi \tan\varepsilon / \tan\mu}{E\beta} \qquad k > \varepsilon$$

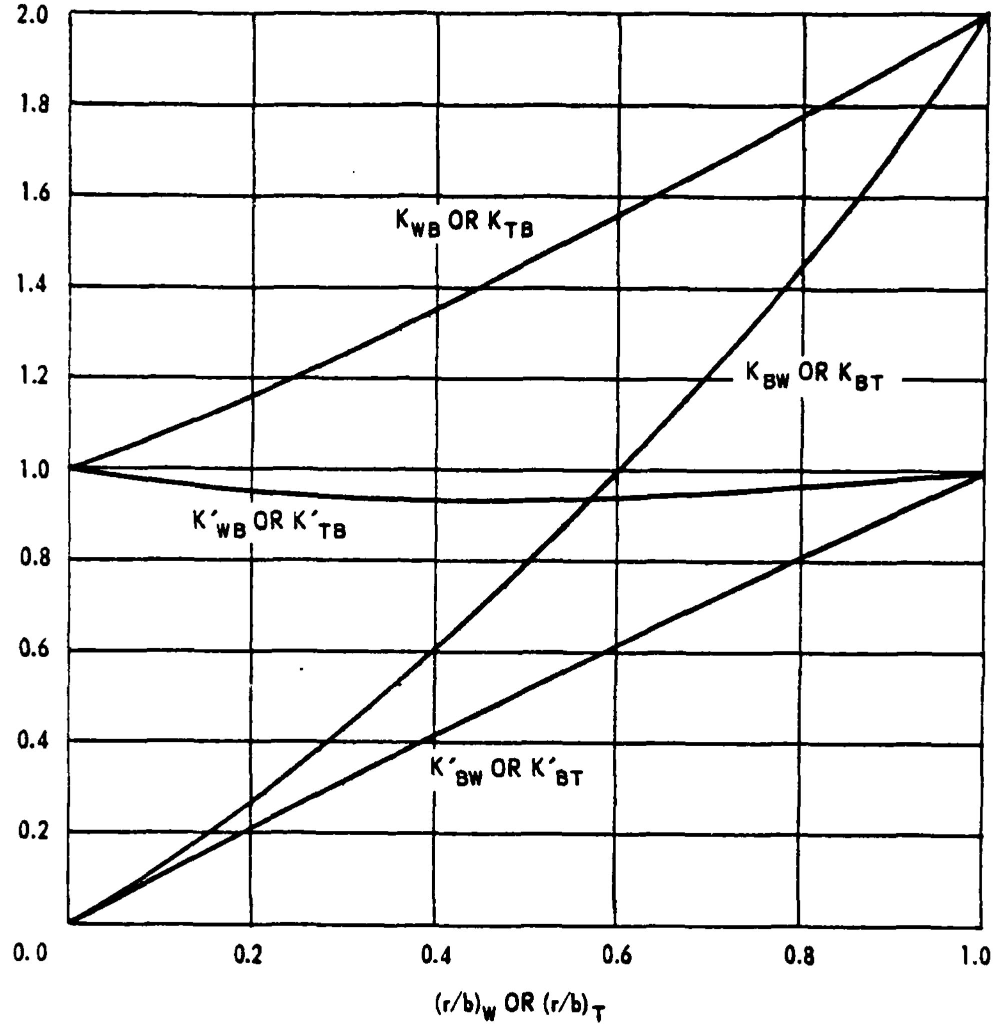


Figure (6-5). Interference factors [12].

Where E is the elliptic integral of the second kind for

$$\sqrt{1 - (\tan\varepsilon/\tan\mu)} \ ,$$

Figure (6) shows the Mach angle μ and sweep angle, ε.

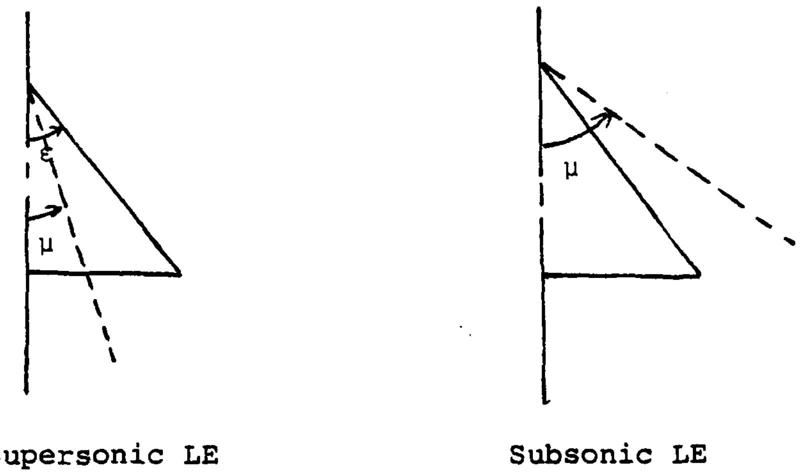


Figure (6-6). Wing leading edge.

The lift of the nose is that obtained from slender body theory. For small angles of attack

$$(C_{N\alpha})_N = 2/\text{rad}.$$

The tail-body combination lift is determined in the same manner as the wing. The above equations are defined for the case where the incidence angle is zero and the angle of attack, (α), is varied. Analogous terms can be defined for the case where the angle of attack is zero and the incidence angle (δ) is varied,

$$k_{B_{(T)}} = \frac{L_{B_{(T)}}}{L_T} = \frac{(C_{L\delta})_{B_{(T)}}}{(C_{L\alpha})_T} \quad ; \qquad \alpha = 0$$

$$k_{T_{(B)}} = \frac{L_{T_{(B)}}}{L_T} = \frac{(C_{L\delta})_{T_{(B)}}}{(C_{L\alpha})_T} \quad ; \qquad \alpha = 0$$

The interference factors $k_{B_{(T)}}$ and $k_{T_{(B)}}$ were also found from slender body theory and are plotted in Figure (6.5).

From the above defnitions the total missile lift curve slope can be found. If the analysis is for small angles of attack so that $L \simeq N$.

$$(N)_{cm} = (N)_N + (N)_{W_{(B)}} + (N)_{B_{(W)}} + (N)_{T_{(B)}} + (N)_{B_{(T)}}$$

in coefficient form,

$$C_N\, q\, S_{reg} = (C_N)_N\, q\, S_{ref} + (C_N)_{W_{(B)}}\, q\, S_W + (C_N)_{B_{(W)}}\, q\, S_W$$

$$+ (C_N)_{T_{(B)}}\, q_T\, S_T + (C_N)_{B_{(T)}}\, q_T\, S_T$$

If the downwash is neglected so that $q_T = q$, and the above equation is differentiated with respect to angle of attack,

$$(C_{N\alpha})_{CM} = (C_{N\alpha})_N + (C_{N\alpha})_{W(B)} \frac{S_W}{S_{ref}} + (C_{N\alpha})_{B(W)} \frac{S_W}{S_{ref}}$$

$$+ (C_{N\alpha})_{T(B)} \frac{S_T}{S_{ref}} + (C_{N\alpha})_{B(T)} \frac{S_T}{S_{ref}}$$

From the definition of the interference factors.

$$(C_{N\alpha})_{CM} = (C_{N\alpha})_N + (C_{N\alpha})_W (K_{W(B)} + K_{B(W)}) \frac{S_W}{S_{ref}}$$

$$+ (C_{N\alpha})_T (K_{T(B)} + K_{B(T)}) \frac{S_T}{S_{ref}} \qquad (6)$$

If the tail is the control surface, a similar development for the control effectiveness, $C_{N\delta}$ yields.

$$(C_{N\delta})_{CM} = (C_{N\alpha})_T (k_{T(B)} + k_{B(T)}) \frac{S_T}{S_{ref}} \quad .$$

D. MISSILE PITCHING MOMENT

From Figure (6-7) the moment about the center of gravity can be found. The centroid of the wing is the location of the center of pressure of a wing alone in supersonic flow. The effect of the wing-body combination is to move the center of pressure aft and as can be seen in Figure (6-7) the center of pressure for the additional lift on the body due to the presence of the wing is aft of this location. Reference [13] has an

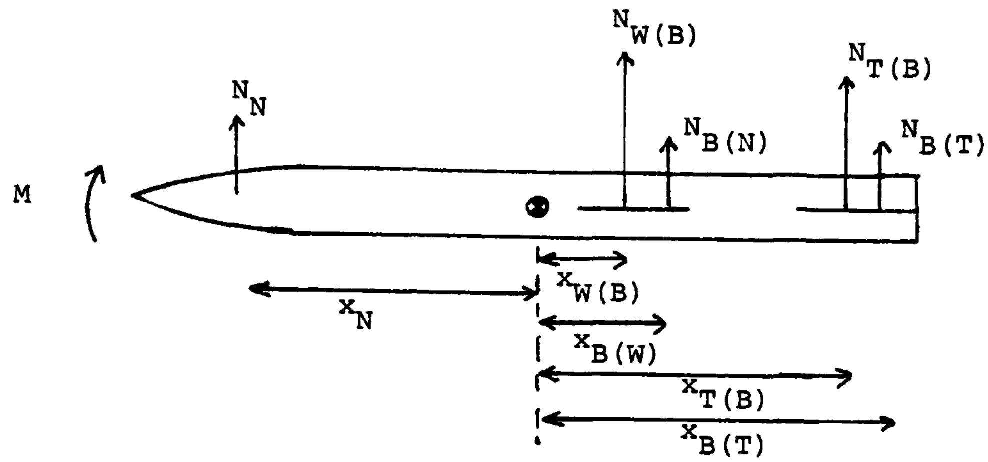


Figure (6-7). Forces Acting on the Missile.

excellent discussion on how to find these centers of pressure. For the purpose of this chapter, which is initial sizing and placement of the lifting surfaces, the center of pressure for both of these forces, $N_{W_{(B)}}$ and $N_{B_{(W)}}$ is taken as the centroid of the wing planform. With this assumption, the moment about the center of gravity is,

$$(M)_{CM} = N_N\, x_N + (N_{W_{(B)}} + N_{B_{(W)}})\, x_W + (N_{T_{(B)}} + N_{B_{(T)}})\, x_T$$

Following the same development as for C_N

$$C_{M\alpha} = (C_{N\alpha})_N \frac{x_N}{D} + (C_{N\alpha})_W (K_{W_{(B)}} + K_{B_{(W)}}) (\frac{x_N}{D}) (\frac{S_W}{S_{ref}})$$

$$+ (C_{N\alpha})_T (K_{T_{(B)}} + K_{B_{(T)}}) (\frac{x_T}{D}) (\frac{S_T}{S_{ref}}) \qquad (7)$$

Also if the tail is the control surface.

$$C_{M\delta} = (C_{N\alpha})_T \, (k_{T(B)} + k_{B(T)}) \left(\frac{x_T}{D}\right) \left(\frac{S_T}{S_{ref}}\right)$$

Ome must be careful in defining the moment arms in the above equations. If a nose up pitching moment is developed in Figure (6-7), the moment arm is positive. Conversely, a negative moment arm means a nose down pitching moment is developed.

E. WEIGHT AND CENTER OF GRAVITY VARIATIONS

From the preceding sections of this chapter, it can be seen that the analysis is normally for one point in the flight profile. Since the launch condition has been defined, the tail sizing can be accomplished for this initial condition. The variation of missile weight and center of gravity is due to propellant burning. For a solid propellant this variation can be quite large. Since no information is available on the propellant at this point in the design, the following guidelines will serve for initial calculations. For air-to-air missiles the propellant is approximately 35 percent of the launch weight. The center of gravity travel is 5 percent of the length. For surface-to-air missiles which must be boosted to flight speed, the propellant weight can be taken to be 48 percent of the launch weight with a corresponding center of gravity travel of approximately 8 percent of the length. These are initial approximations taken from historical data and can be refined later in the design process.

VII. LIFTING SURFACE DESIGN

From the analysis of wing lift and drag in Chapter 6, it can be seen that the performance of a wing will vary with planform. Up to this point the lifting surfaces have been considered delta planforms with zero taper ratio. This is not necessarily the optimum planform since it was taken from a historical average and does not apply to a specific missile. This chapter deals with the sizing, placement and planform definition of the missile.

A. WING PLACEMENT

The wing placement on the missile depends upon the type of control used. For canard control the wing (aft surface) is normally fixed as far aft as possible for stability purposes. For a wing control or tail control missile, where the wing is near the center of gravity, the wing placement becomes more critical and depends upon the stability margin required. Since the drag during the cruise segment includes the drag due to lift, one method to minimize drag would be to place the wing such that zero lift is produced on the tail during cruise. The moment about the center of gravity is zero for trimmed flight, thus equation (7) yields, for $(C_N)_T = 0$.

$$x_W = -\frac{(C_{N\alpha})_N \; x_N \; S_{ref}}{(C_{N\alpha})_W \; S_W \; (K_{W(B)} + K_{B(W)})}$$

B. MANEUVER LOAD FACTOR

Regardless of the type of missile being designed, it will be required to maneuver in order to intercept its intended target. For an air-to-air or surface-to-air missile the level of this maneuver may be quite large. The maneuver load factor required was found in Chapter 3. The maximum maneuver the missile can sustain depends upon the maximum trimmed normal force the missile can develop.

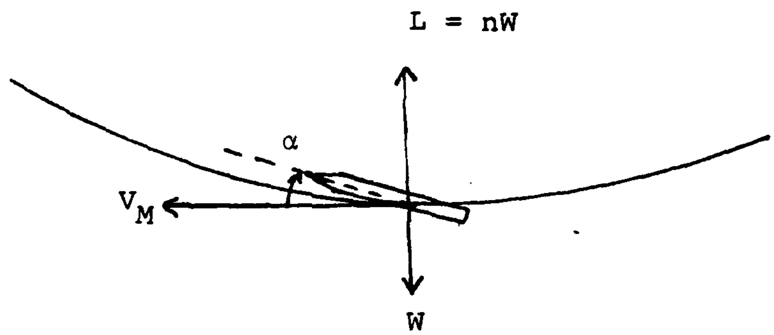


Figure (7-1). Sustained maneuver of a missile.

From Figure (7-1) the force developed by a missile in a constant acceleration turn is

$$L = nW \tag{1}$$

n = maneuver load factor

Small angles of attack are assumed for which the lift and normal force are approximately equal. This approximation is good for angles of attack of up to 10 degrees, and above this value of maximum trimmed angle of attack the linear theory becomes inaccurate. With this assumption for now, equation (1) becomes,

$$L = N = nW$$

$$(C_{N\alpha})\alpha\; q\; S_{ref} = nW \tag{2}$$

$$(C_{N\alpha})_{required} = \frac{nW}{(\alpha)_{max}\; q\; S_{ref}}$$

Equation (2) gives the lift-curve slope required to develop the required normal force at a trimmed angle of attack, $(\alpha)_{max}$. The lift curve slope developed is given by equation (6) in Chapter 6.

$$(C_{N\alpha})_{CM} = (C_{N\alpha})_N + (C_{N\alpha})_W (K_{W(B)} + K_{B(W)}) \frac{S_W}{S_{ref}} + (C_{N\alpha})_T (K_{T(B)} + K_{B(T)}) \frac{S_W}{S_{ref}} \tag{3}$$

As discussed earlier the values of the interference factors depend upon the wing planform. Typical values of $(K_{W(B)} + K_{B(W)})$ and $(K_{T(B)} + K_{B(T)})$ are from 1.5 to 2.0. As a conservative estimate a value of 1.5 is assumed. Equation (3) then becomes,

$$(C_{N\alpha})_{CM} = (C_{N\alpha})_N + 1.5\; (C_{N\alpha})_W \frac{S_W}{S_{ref}} + 1.5\; (C_{N\alpha})_T \frac{S_T}{S_{ref}} \tag{4}$$

Selecting supersonic leading edges,

$$(C_{N\alpha})_W = (C_{N\alpha})_T = 4/\beta$$

Therefore

$$(C_{N\alpha})_{CM} = (C_{N\alpha})_N + \frac{6}{\beta\, S_{ref}} (S_W + S_T)$$

If the complete missile lift-curve slope is set equal to the required lift-curve slope, the lifting surface area required to maintain the maneuver load factor can be found, using equation (4).

$$(S_W + S_T)_{req} = [(C_{N\alpha})_{req} - (C_{N\alpha})_N] \frac{\beta\, S_{ref}}{6}$$

Let

$$K = \frac{(S_W + S_T)_{req}}{(S_W + S_T)_{baseline}}$$

If the same ratio of wing to control surface area is kept to minimize stability perturbations, the new wing and tail area are,

$$S_W = K(S_W)_{baseline}$$

$$S_T = K(S_T)_{baseline}$$

The above analysis assumes a linear variation of $C_{N\alpha}$ which is good for small angles of attack. A more precise analysis will be performed in Chapter 9. The above analysis should be performed at the expected encounter conditions.

1. <u>Design Example (Maneuver Load Factor)</u>

Since a canard control was chosen for the design example the canard and wing position are fixed as far forward and aft as possible. The analysis is done for a conservative Mach number of 2.5 after the missile has slowed from its cruise velocity due to the maneuver. From previous results,

$$n = 31 \text{ g's}$$

$$(S_W + S_C)_{baseline} = 9.02 \text{ ft}^2$$

$$W_G = 794.83 \text{ lbs}$$

If the missile is required to maneuver at one-half its powered range, and the propellant weight is 35 percent of the launch weight, the maneuver weight becomes

$$W = 655.73 \text{ lbs}$$

The dynamic pressure for $M_M = 2.5$ and at 10,000 feet altitude is

$$q = \frac{1}{2} \rho V_M^{\ 2}$$

$$q = 6369.84 \text{ lbs ft}^2$$

The required lift-curve slope becomes for $(\alpha_{max}) = 10$ degrees $= .1745$ rad.

$$(C_{N\alpha})_{req} = 33.5311 \text{ per rad.}$$

The required lifting surface area is;

$$(S_W + S_C)_{req} = [33.5311-2] \frac{\beta S_{ref}}{6} = 6.57 \text{ ft}^2$$

Therefore $K = 0.7284$.

The required wing and canard sizes to achieve the maneuver are;

$$S_W = (7.52)(.7284) = 5.48\ \text{ft}^2$$
$$S_C = (1.50)(.7284) = 1.09\ \text{ft}^2$$

C. TAIL SIZING

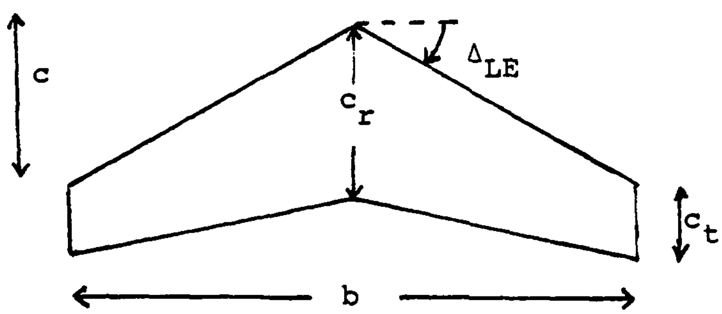
For a wing-tail combination, the primary concern in the sizing of the tail is the static stability of the missile. The missile becomes more stable as the mission proceeds, since the center of gravity moves forward as the propellant burns. As the missile becomes more stable, control of the missile becomes sensitive. If the tail is sized for zero static stability at launch, the missile control will remain more effective during flight. This is the best condition possible without the use of some form of stability augmentation system at launch. Therefore, at launch $C_{N\alpha} = 0$.

$$0 = (C_{N\alpha})_N x_N + (C_{N\alpha})_W x_W \frac{S_W}{S_{ref}} (K_{W(B)} + K_{B(W)}) + (C_{N\alpha})_T x_T \frac{S_T}{S_{ref}} (K_{T(B)} + K_{B(T)}) \tag{5}$$

With the lifting surface area fixed due to the maneuver load factor, the tail can be sized to satisfy equation (5). As can be seen the position depends highly on the moment arms that the lift forces act through. Since the missile length has not been fixed at this point in the design and may vary due to propulsion requirements, this analysis will be completed later.

D. WING PLANFORM

The wing planform is specified by the leading edge sweep, Δ_{LE}, taper ratio, λ, aspect ratio, AR and planform area S_W. The planform area was fixed due to maneuvering requirements in a previous section. This section is concerned with defining the remaining planform parameters. Figure (7-2) is the wing planform and the equations used to define these parameters.



$$AR = b^2/s$$

$$\lambda = c_t/c_r$$

$$c_r = \frac{2\ s}{b(1+\lambda)}$$

$$\bar{c} = \frac{2}{3}\ c_r\ \left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right)$$

$$c = \frac{b}{2}\ \tan\ \Delta_{LE}$$

Figure (7-2). Planform geometry.

The value of the lift-curve slope used previously was derived from linear theory and is applicable only to simple planforms. For the purpose of this section, which will include low aspect ratio wings with supersonic and subsonic leading edges, Figures (7-3) and (7-4) are used. These figures have been corrected for 3-D effects.

1. <u>Effect of Taper Ratio and Leading Edge Sweep</u>

The lift and drag characteristics of the wing are the primary parameters of interest. The objective inwing design is

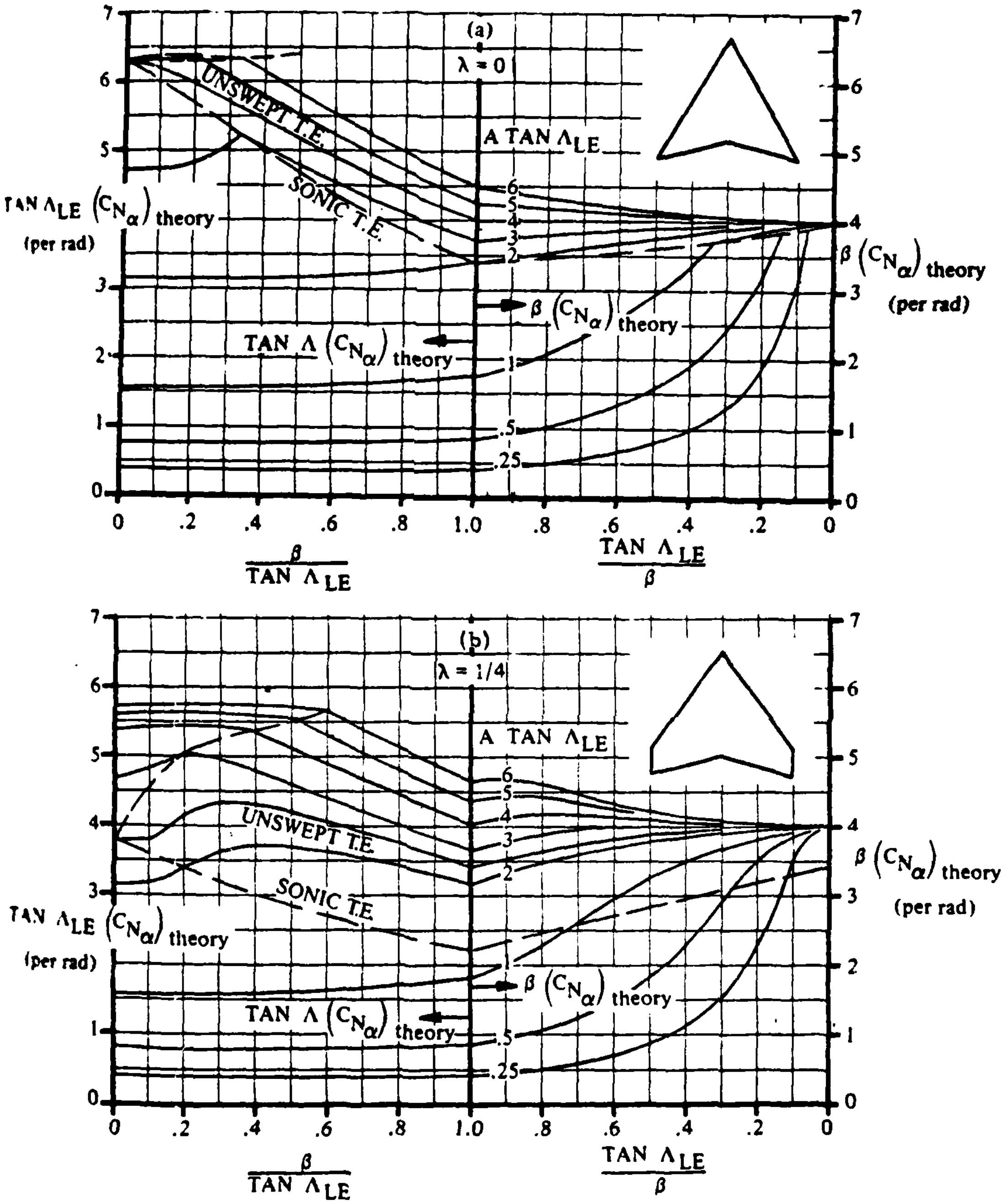
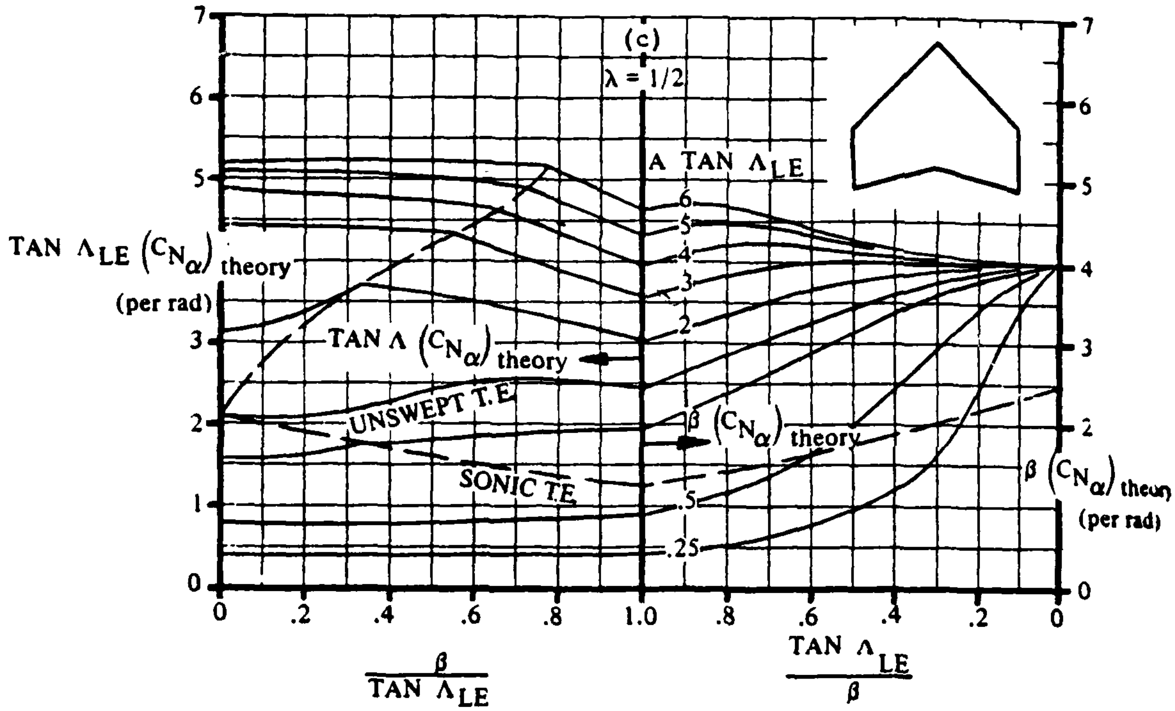


Figure (7-3). Theoretical wing lift curve slope [12].



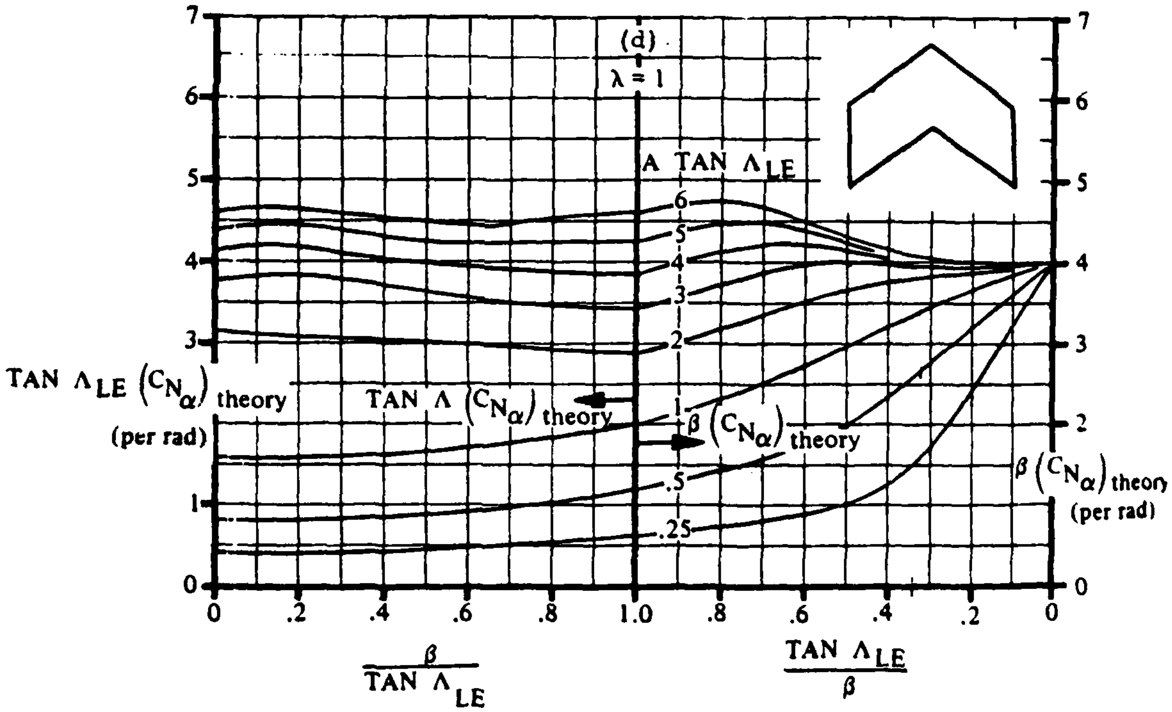


Figure (7-4). Lift curve slope continued [12].

is to obtain maximum lift with minimum drag. It will be shown that these objectives are usually conflicting; therefore, some compromise, or optimum, planform must be found. From Chapter 6 the equations for the drag of a wing in supersonic flow are found. The skin friction drag depends upon the mean geometric chord. Equation (3) in Chapter 6 indicates a larger mean geometric chord would result in less skin friction drag for a fixed area. The mean geometric chord can be expressed in terms of taper ratio as follows,

$$\bar{c} = \frac{2}{3} \frac{2\,s}{b(1+\lambda)} \left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right)$$

$$\bar{c} = \frac{4}{3} \sqrt{\frac{s}{AR}} \left[\frac{1+\lambda+\lambda^2}{(1+\lambda)^2}\right]$$

This equation leads to a zero taper ratio to maximize $\bar{c}$ and reduce skin friction if the surface area and aspect ratio were fixed. The wave drag is constant for supersonic leading edges, and decreases when the leading edge goes subsonic or the leading edge is behind the mach line. The lift capabilities also decrease as the leading edge goes subsonic.

As stated earlier this leads to conflicting performance since the objective is to minimize drag while maximizing lift. At this point an example best illustrates the results of varying taper ratio and leading edge sweep. The lift - curve slope is derived using the methods of reference (1). Figures (7-3) and (7-4) are from reference [12] and are used to find the supersonic linear lift corrected for 3-D flow effects. The drag methods of Chapter 5 are used to determine the drag characteristics.

2. Example

For a fixed wing area of 4 ft^2 and an aspect ratio of 2 the lift curve slope and drag were determined for a flight Mach number of M= 2. This Mach number corresponds to a sonic leading edge sweep of 60°. The wing leading edge sweep was varied from zero to 75° for taper ratios of 0, 1/2 and 1. The results are plotted in Figures (7-5) and (7-6).

From this example certain generalizations can be made. From Figure (7-5) it can be seen that the drag is relatively insensitive to taper ratio. There is a reduction in drag for increased leading edge sweep. For this example there is approximately a 6 percent drag reduction for every five degree increase beyond the sonic value. Figure (7-6) indicates that the effect of decreasing the taper ratio is to delay the drop in the lift curve slope of the wing. From this example a general guideline would be to fix the leading edge sweep 5 degrees beyond the sonic value and the taper ratio at zero. This would provide a 6 percent reduction of wave drag while maintaining the maximum lifting capabilities of the wing.

3. Effect of Varying Aspect Ratio

The result of increasing aspect ratio is an increase in the lift-curve slope of the wing [12]. The aspect ratio is given by,

$$AR = b^2/s$$

For a zero taper ratio wing this becomes;

$$AR = 2b/c_r \tag{6}$$

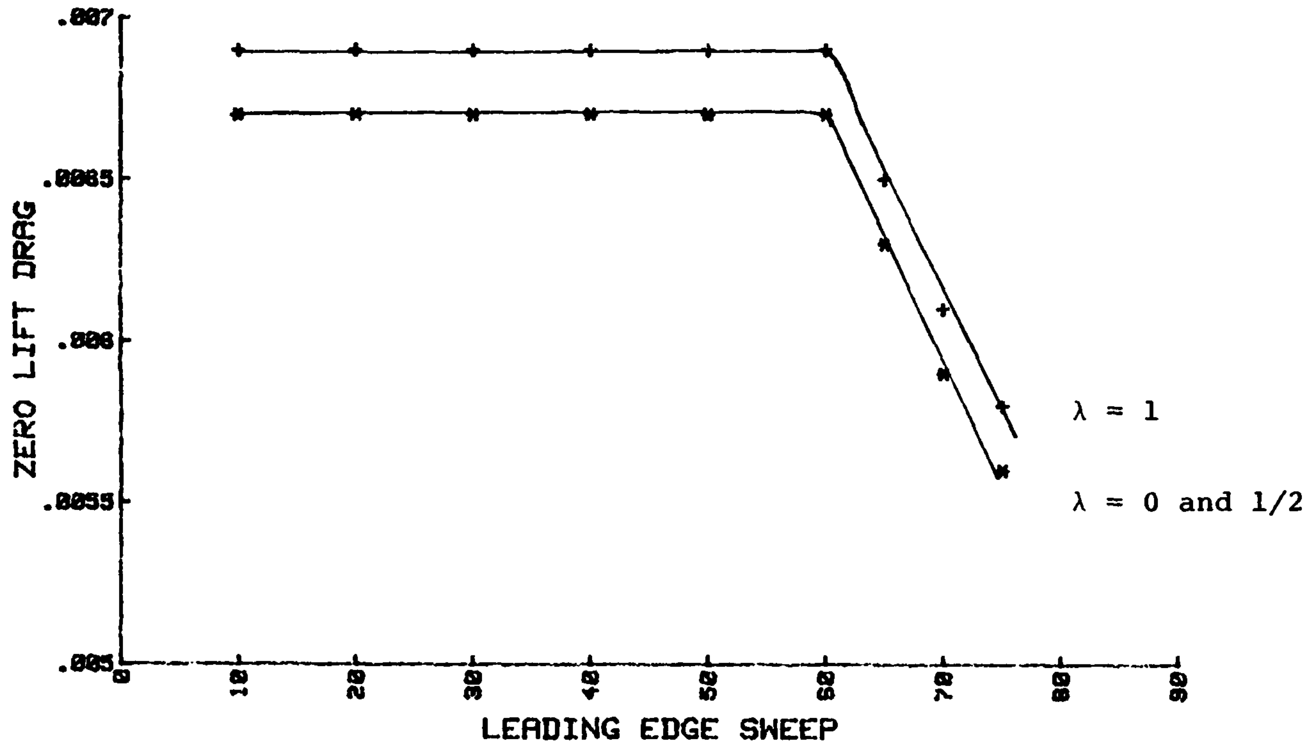


Figure (7-5). Effect of λ on drag.

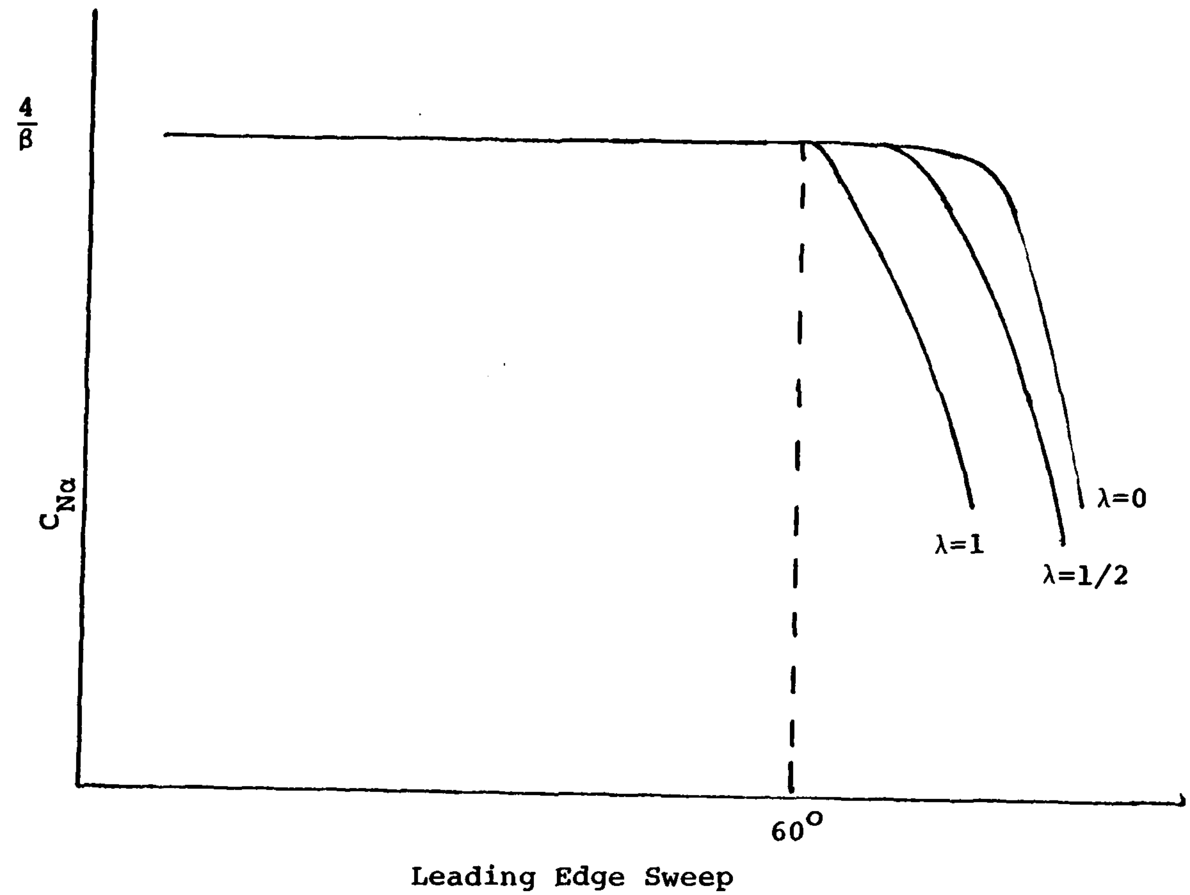


Figure (7-6). Effect of λ on lift curve slope.

From equation (6) it can be seen that increasing aspect ratio results in a corresponding increase in wing span for a given root chord. Missiles are normally span limited, due to launcher constraints; therefore, there is a maximum span which can be accomodated. The drag of the wing again is in conflict with the lift since increasing aspect ratio decreases the mean geometric chord for a given span and therefore increases skin friction drag. A compromise wing AR must be found which considers both the lift and the drag characteristics. For a discussion of optimum aspect ratio, the following functions are defined for convenience:

$$F = F_1 + F_2 \doteq \text{Lift-drag function} \tag{7}$$

where

$$F_1 \equiv \frac{C_{D_0}}{(C_{D_0})_{max}} \doteq \text{Normalized drag function}$$

$$F_2 \equiv \frac{1/C_{N\alpha}}{1/(C_{N\alpha})_{min}} \doteq \text{Normalized lift function}$$

From equation (7) if F is plotted over the allowable range of aspect ratio, a minimum value of the lift-drag function fixes the desired aspect ratio. This aspect ratio corresponds to minimizing the drag function, F_1, while maximizing the lift function, F_2. For convenience the abscissa is plotted as $\bar{c}/\bar{c}_{(max)}$ as shown in Figure (7-7).

From Figure (7-7) the optimum mean geometric chord corresponds to point A.

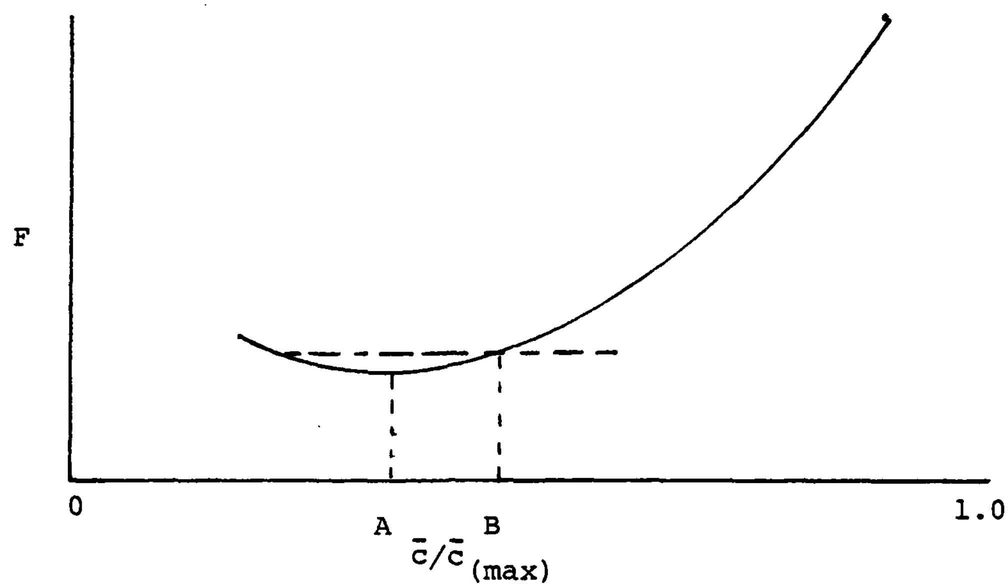


Figure (7-7). Lift-drag function.

$$\bar{c} = \left(\frac{\bar{c}}{\bar{c}_{max}}\right)_A \quad \bar{c}_{max}$$

The aspect ratio is then given by

$$c_r = \frac{3}{2}\,\bar{c}$$

$$b = 2s/c_r$$

$$AR = b^2/s$$

As mentioned earlier a missile is normally span limited. The plot of the lift-drag function F is normally fairly flat on the left, or for $\bar{c}/\bar{c}_{(max)}$ approaching zero. For this reason point B may be chosen as the optimum since F varies very little up to this region. Point B corresponds to increased chord and decreased span.

4. Design Example (Wing Planform)

From the previous analysis the following parameters were defined.

$$M_M = 3.0$$

$$S_W = 5.48 \text{ ft}^2$$

If the leading edge sweep is fixed 5 degrees behind the mach line.

$$\mu = \sin^{-1} \frac{1}{M} = 19.5^\circ$$

$$\Delta_{LE} = 95 - \mu = 75.5^\circ$$

$$\lambda = 0$$

The planform table becomes

AR	b	c_r	$\bar{c}$	$K_{W(B)}$	$K_{B(W)}$
2.0	3.31	3.31	2.21	1.17	.26
1.5	2.87	3.82	2.55	1.19	.30
1.0	2.34	4.68	3.12	1.22	.35
.75	2.03	5.40	3.60	1.24	.40
.50	1.66	6.62	4.41	1.29	.48
.25	1.17	9.36	6.24	1.36	.62

The wave drag is constant and is given by,

$$C_{D_W} = 4 \cot \Delta_{LE} \left(\frac{t}{c}\right)^2 \frac{S_W}{S_{ref}}$$

$$C_{D_W} = .0094$$

AR	C_{D_f}	C_{D_0}	AR tan Δ_{LE}	$\frac{\beta}{\tan \Delta_{LE}}$	$(C_{N\alpha})_W (K_{W(B)} + K_{B(W)})$
2.0	.0303	.0397	7.73	.73	2.1137
1.5	.0296	.0390	5.80	.73	1.9845
1.0	.0288	.0382	3.87	.53	1.8271
.75	.0282	.0376	2.90	.73	1.7813
.50	.0274	.0368	1.93	.73	1.4809
.25	.0260	.0354	.97	.73	.7937

AR	$\bar{c}/\bar{c}_{max}$	F_1	F_2	F
2.0	.35	1.0000	.3755	1.3755
1.5	.41	.9824	.3999	1.3823
1.0	.50	.9622	.4344	1.3966
.75	.58	.9471	.4456	1.3927
.50	.70	.9270	.5360	1.4630
.25	1.00	.8917	1.0000	1.8917

From Figure (7-8) it can be seen that the lift-drag function remains relatively constant up to $\bar{c}/\bar{c}_{max} = .58$. Since the object is to make the span as small as possible this point is taken. The wing planform becomes,

$$\bar{c} = .58\ \bar{c}_{max} = 3.62 \text{ ft} = 43.44 \text{ in}$$

$$c_r = 5.43 \text{ ft} = 65.16 \text{ in}$$

$$b = 2.02 \text{ ft} = 24.24 \text{ in}$$

$$c = 3.90 \text{ ft} = 46.80 \text{ in}$$

$$AR = 0.74$$

5. <u>Design Example (For Canard Planform)</u>

From prèvious analysis and development, the following parameters have been defined:

$$M = 3.0$$

$$S_c = 1.09 \text{ ft}^2$$

$$(t/c)_c = 0.03$$

If the leading edge sweep is set 5 degrees behind the sonic value and the taper ratio is set to zero, the following planform table results.

$$\Delta_{LE} = 75.5^{\circ}$$

$$\lambda = 0$$

AR	b	c_r	c	$K_{W(B)}$	$K_{B(W)}$
2.5	1.63	1.34	.89	1.29	.52
2.0	1.48	1.47	.98	1.31	.55
1.5	1.28	1.70	1.14	1.35	.59
1.0	1.04	2.10	1.40	1.47	.76
.5	.74	2.94	1.96	1.51	.90
.25	.52	4.19	2.79	1.59	1.02

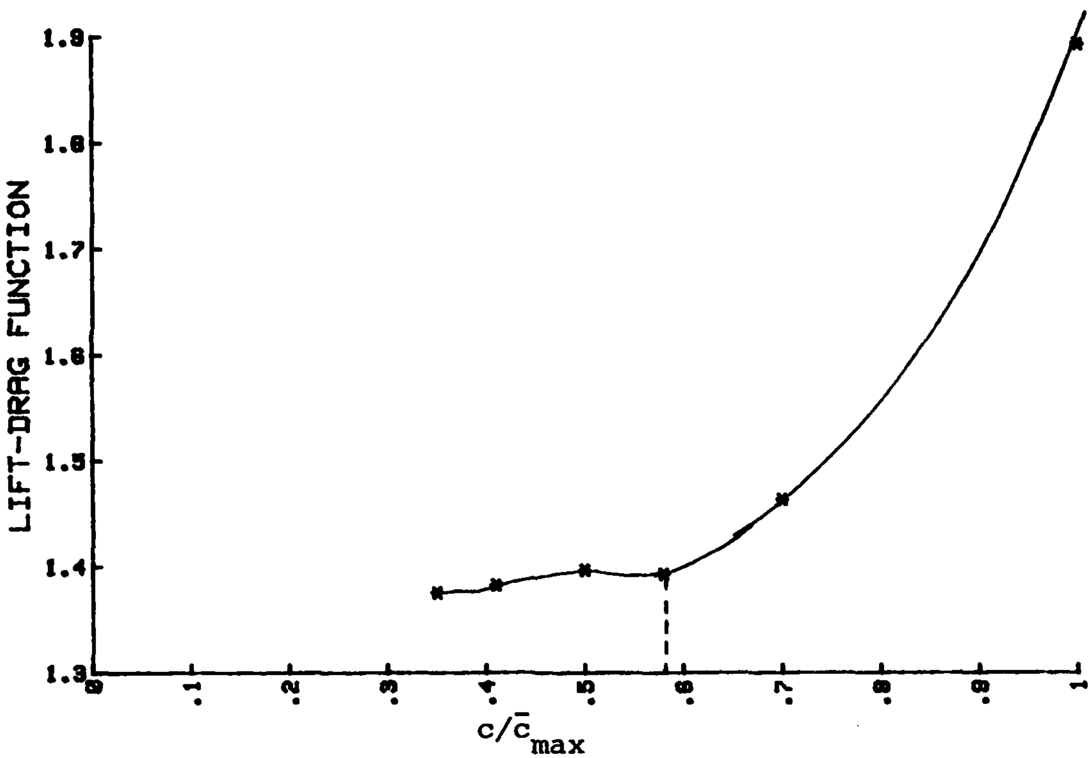


Figure (7-8). Wing lift-drag function.

AR	C_{D_f}	C_{D_0}	AR tan Δ_{LE}	$\frac{\beta}{\tan \Delta_{LE}}$	$C_{N\alpha}(k)$
2.5	.0069	.0087	9.67	.73	
2.0	.0067	.0085	7.73	.73	2.7900
1.5	.0067	.0085	5.80	.73	3.6339
1.0	.0064	.0082	3.87	.73	2.5952
.5	.0061	.0079	1.93	.73	2.0880
.25	.0058	.0076	.97	.73	1.0124

AR	$\bar{c}/\bar{c}_{max}$	F_1	F_2	F
2.0	.35	1.0000	.3628	1.3628
1.5	.41	1.000	.3844	1.3844
1.0	.50	.9647	.3901	1.3557
.5	.70	.9294	.4849	1.4143
.25	1.00	.8941	1.0000	1.8941

From Figure (7-9) it is seen that there is a minimum of the lift-drag function at $c/\bar{c}_{max} = 0.5$. The optimum canard is then,

$$\bar{c} = 0.5\ \bar{c}_{max} = 1.40 \text{ ft} = 16.80 \text{ in}$$

$$c_r = 2.09 \text{ ft} = 25.08 \text{ in}$$

$$b = 1.04 \text{ ft} = 12.48 \text{ in}$$

$$AR = 0.99$$

$$c = 2.01 \text{ ft} = 24.12 \text{ in}$$

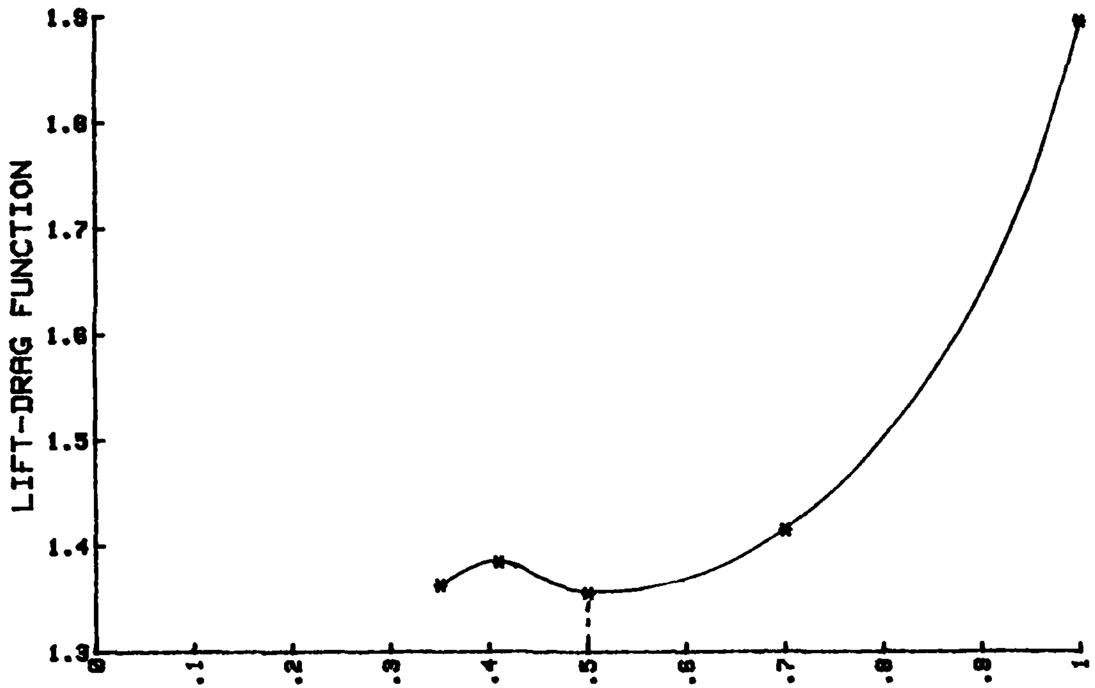


Figure (7-9). Canard lift-drag function.

E. DESIGN EXAMPLE (REVISION OF ZERO LIFT-DRAG AND LIFT-CURVE SLOPE)

Wing: $c = 3.62$ ft

$c_f = .0014$

$(C_{D_0})_W = .0750$

Canard: $\bar{c} = 1.40$ ft

$c_f = .0016$

$(C_{D_0})_c = .0166$

Body: $(C_{D_0})_B = .2292$

The complete missile C_{D_0} including the interference factor of 1.25, is now 0.4010. From the previous calculation of the baseline zero lift-drag coefficient, the drag has been reduced by 14.6 percent.

From equation (6) in Chapter 6 the lift-curve slope is now

$$C_{N\alpha} = 25.17/\text{rad}$$

Figure (7-10) is the missile design to this point.

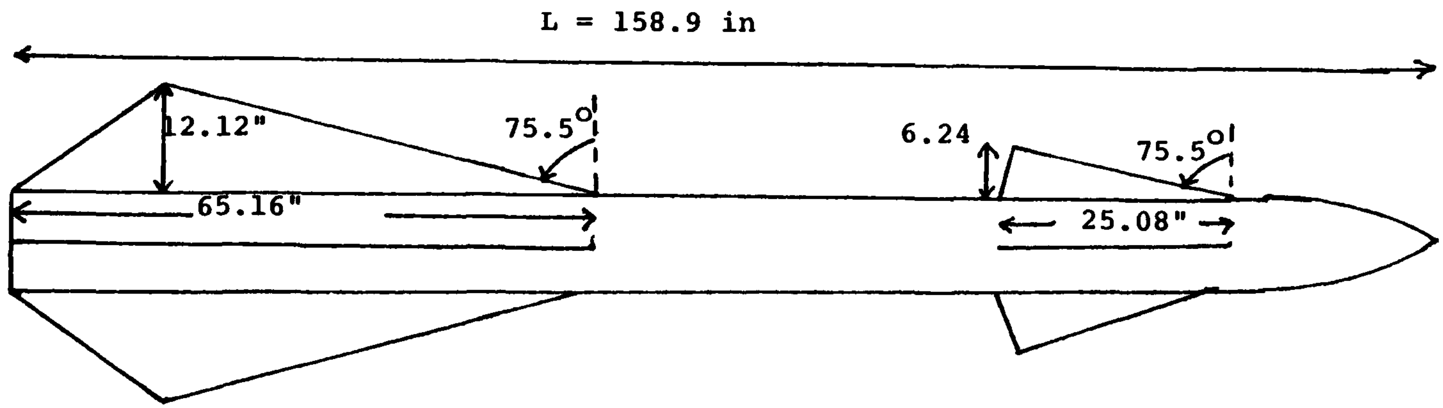


Figure (7-10). Design with "optimum" wings.

VIII. PROPULSION REQUIREMENTS

The following discussion presents a method for preliminary sizing of a solid rocket motor for a boost-sustain trajectory of an air launched or a surface launched tactical missile. The analysis consists of sizing the booster from incremental velocity considerations and sizing, the sustainer for the maximum range required at the operational altitude. The method assumes a constant acceleration boost and a constant altitude cruise.

A. BOOSTER INITIAL SIZING

Since the control system cannot respond properly while in the boost phase of flight, it becomes important to make the boost time as short as possible. The limiting factor for boost time is the maximum axial acceleration the airframe and components can withstand. This maximum acceleration is normally around 30 g's. The boost time then becomes,

$$t_b = \int_{V_1}^{V_2} \frac{dV}{a}$$

For constant acceleration,

$$t_b = \frac{V_2 - V_1}{a} = \frac{\Delta V_B}{a} \qquad (1)$$

The incremental velocity during boost, ΔV_B, can be derived from the equations of motion.

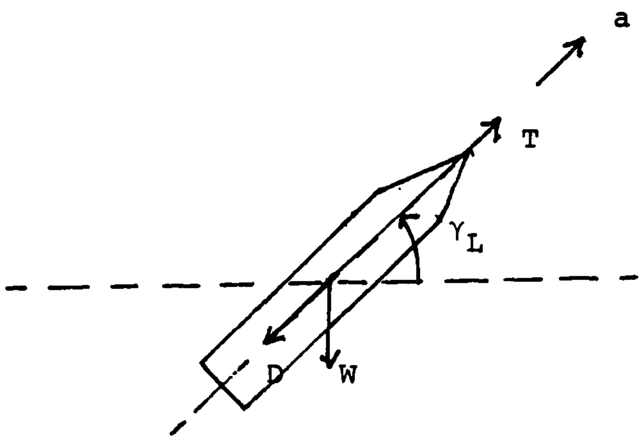


Figure (8-1). Forces acting on the missile.

If during the boost phase the thrust, drag and launch angle are considered constant, the axial acceleration of the missile is constant and may be written as:

$$m \frac{dV}{dt} = T - D - W \sin \gamma_L$$

$$dV = g(\frac{T-D}{W})dt - g \sin \gamma_L \, dt$$

If the launch velocity is V_1 and the velocity at the end of boost is V_2,

$$\int_{V_1}^{V_2} dV = \int_0^{t_b} g(\frac{T-D}{W})dt - \int_0^{t_b} g \sin \gamma_L \, dt \qquad (2)$$

The vehicle weight in equation (2) is a function of time. If the propellant weight is given by W_p, and the propellant grain burn is linear with time, the missile weight can be expressed as,

$$W = W_L - W_p\left(\frac{t}{t_b}\right)$$

where W_L = Launch weight.

Equation (2) then becomes,

$$\Delta V_B = V_2 - V_1 = g(T - D)\int_0^{t_b} \frac{t_b dt}{(W_L t_b - W_p t)} - g \sin \gamma_L\, t_b$$

Integrating the first term yields,

$$\Delta V_B = \frac{g(T - D)t_b}{W_p}\, \ell n \left[\frac{(W_L - W_p)t_b}{W_L t_b}\right] - g \sin \gamma_L\, t_b$$

Since the empty weight is given by

$$W_E = W_L - W_p$$

The incremental velocity can be written as

$$\Delta V_B = \frac{g(T - D)t_b}{W_p}\, \ell n \frac{W_L}{W_E} - g \sin \gamma_L\, t_b \qquad (3)$$

A first estimate of propellant weight can be made if the drag is assumed zero in equation (3), and $I_{sp} = Tt_{b/W_p}$

$$\Delta V_B = g\, I_{sp}\, \ell n \frac{W_L}{W_E} - g \sin \gamma_L\, t_b \qquad (4)$$

In the above expression the specific impulse, I_{sp}, is characteristic of the propellant chosen and can be found from historical data, or a specific propellant value may be used.

Equation (4) can then be solved for $\frac{W_L}{W_E}$ and the first estimate of propellant weight, W_p, can be found as follows,

$$W_p = W_L(1 - \frac{W_E}{W_L})$$

With the propellant weight and specific impulse known, the total impulse and average thrust required for boost can be found.

$$I_T = I_{sp} W_p$$

$$T = \frac{I_T}{t_b}$$

With the thrust known and an average value of drag assumed, equation (3) can be iterated for an improved estimate of the propellant weight needed.

The final result is used to calculate the booster combustor volume and length.

$$V_B = W_p/\rho_p \eta_p$$

where n_p = volumetric packing factor

$$L_B = 4V_B/\pi D_c^2$$

The combustor diameter is limited by the missile maximum diameter and is a design choice. The propellant density, ρ_p, and volumetric packing factor, n_p, are determined from historical data or given for a specific propellant.

B. SUSTAINER INITIAL SIZING

The sustainer thrust required to maintain cruise is the driving factor in the sustainer motor sizing. For initial sizing purposes, a level, constant velocity cruise segment is assumed. In this analysis the thrust required is equal to the aerodynamic drag developed by the missile. The performance requirements determine the maximum range, operating altitude, and velocity of the missile. From these requirements the sustainer burn time, t_s, can be determined.

$$t_s = \frac{R_{max} - S_B}{V_M}$$

where S_B = distance traveled during boost.

Since sustainer thrust is equal to drag, $T_S = D$, the total impulse required becomes,

$$(I_T)_S = Dt_s$$

The sustainer nozzle is sized for the operational altitude of the missile. The thrust coefficient, C_{Fd}, can be expressed as;

$$C_{Fd} = C_d\lambda \sqrt{\frac{2\gamma^2}{\gamma-1} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \left[1 - \left(\frac{p_0}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

The constant, Cd, is the nozzle efficiency and has been determined from historical data to be 0.96. The nozzle half angle correction, λ, is given by;

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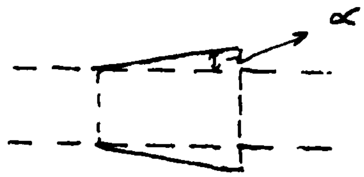
$$\lambda = (1 + \cos \alpha)/2$$



where α is the nozzle half angle. A nominal value used in many designs is 15°. Larger values of α give significant non-axial flow components in the nozzle. Values less than 15° give large nozzle lengths and therefore contribute to excessive missile weights. The combustion chamber pressure is also a design choice. A lower usable value of P_c is 200 psia for sustainers and 500 psi for boosters. The chamber pressure cannot exceed the maximum expected operating pressure of the missile (MEOP).

The thrust of the sustainer can be expressed as a function of the thrust coefficient, chamber pressure, P_c, and throat area, A_t. The throat area required to deliver the required sustainer thrust can be determined from

$$T_s = C_{Fd}\, P_c\, A_t$$

The nozzle area ratio is a function of the pressure ratio P_0/P_c, where P_0 is the ambient pressure if the nozzle expands the flow fully.

$$\frac{A_e}{A_t} = \frac{1}{M_e} \left\{ \frac{2}{\gamma+1} \left[1 + \left(\frac{+1}{2}\right) M_e^{2} \right] \right\}^{\frac{\gamma+1}{2(\gamma-1)}}$$

where
$$\frac{P_0}{P_c} = \left[1 + \left(\frac{\gamma-1}{2}\right) M_e^{2} \right]^{-\frac{\gamma}{\gamma-1}}$$

From the previous equation the exit area can be determined. From the throat and exit diameters, the nozzle length is found by

$$L_n = \frac{D_e - D_t}{2 \tan \alpha}$$

At this point in the design the nozzle exit area and length should be checked to see if they exceed any specifications on the missile; i.e., the nozzle exit area must be less than the base area of the missile.

Finally, the delivered specific impulse is typical of the propellant chosen for the sustainer. The propellant weight is then,

$$W_p = \frac{(I_T)_s}{I_{sp}}$$

The sustainer combustor volume and length are then determined in the same manner as the booster. The equations concerning the sustainer nozzle also apply to the booster nozzle with the appropriate booster areas, pressures and thrust substituted.

C. ROCKET MOTOR CHAMBER PRESSURE

As indicated earlier the delivered thrust increases with increasing chamber pressure, P_c; however, the wall thickness in the rocket motor depends upon the expected operating pressure within the chamber. If the wall thickness is t inches, and the yield stress of the casing material is σ_y, it can be shown that the thickness required of the motor casing is given by,

$$t = \frac{P_{max}\, r}{\sigma_y} \tag{5}$$

where r is the chamber radius, and P_{max} is the maximum chamber pressure, which is taken to be 1.2 P_c to allow for variations within the propellant. From equation (5) the weight of the motor casing can be determined if the casing is cylindrical and $t << r$

$$W_c = \rho_c V_c = 2\pi r \ell_c t \rho_c$$

Substituting for t

$$W_c = \frac{2.4\pi r^2 \ell_c \rho_c P_c}{\sigma_y} \tag{6}$$

The specific impulse of the rocket motor is given by.

$$I_{sp} = \frac{V_j}{g_c} = \frac{1}{g_c} \left\{ 2g_c \left(\frac{\gamma}{\gamma-1}\right) R\, T_0 \left[1 - \left(\frac{P_0}{P_c}\right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{1/2} \tag{7}$$

From equations (6) and (7), it can be seen that a compromise must be made in selecting the chamber pressure; since increasing P_c increases the specific impulse but also increases the casing weight. An attempt must be made to find an optimum operating pressure.

If the rocket motor weight consists of the nozzle, propellant and casing,

$$W_M = W_N + W_P + W_C \tag{8}$$

and the total impulse, which is constant is given by,

$$I = Tt_b = I_{sp} W_p$$

The optimum chamber pressure can be found by minimizing the weight and maximizing the impulse.

$$\frac{d}{dp_c} \left(\frac{W_M}{I}\right) = \frac{d}{dp_c} \left(\frac{W_M}{I_{sp} W_p}\right) = 0$$

differentiating yields,

$$\frac{1}{I_{sp}} \frac{d}{dp_c} \left(\frac{W_M}{W_p}\right) - \frac{W_M}{W_p} \frac{d(1/I_{sp})}{dp_c} = 0$$

$$\frac{1}{I_{sp}} \frac{d}{dp_c} \left(\frac{W_M}{W_p}\right) - \frac{W_M}{W_p I_{sp}^2} \frac{d I_{sp}}{dp_c} = 0 \tag{9}$$

From equation (8)

$$\frac{W_M}{W_p} = \frac{W_c}{W_p} + \frac{W_N}{W_p} + 1 \tag{10}$$

Substituting equation (10) into equation (9),

$$\frac{1}{W_p} \frac{dW_c}{dp_c} - \frac{W_c}{W_p^2} \frac{dW_p}{dp_c} - \frac{W_N}{W_p^2} \frac{dW_p}{dp_c} - \frac{W_M}{W_p I_{sp}} \frac{d I_{sp}}{dp_c} = 0$$

Substituting equations (12) and (13) into equation (11)

$$\frac{2.4\rho_c\, W_p}{\rho_p\, \sigma_y} - \frac{W_p RT_0}{g_c\, I_{sp}^{\ 2}\, p_c} \left(\frac{p_o}{p_c}\right)^{\frac{\gamma-1}{\gamma}}$$

Substituting for $g_c\ I_{sp}^{\ 2}$ in the above equation yields,

$$\frac{\gamma-1}{2\gamma} \quad \frac{1}{\left[\left(\frac{p_0}{p_c}\right)^{(1-\gamma)/\gamma} -1\right] p_c} - \frac{2.4}{\rho_p}\left(\frac{\rho c}{\sigma_y}\right) = 0 \tag{14}$$

If a propellant and casing material are chosen, equation (14) can be solved for the chamber pressures, p_c, which minimizes W_M/I . One interesting feature of equation (14) is that there is a minimum yield strength to density ration $\frac{\sigma_Y}{\rho_c}$ that will yield a usable chamber pressure, furthermore this optimization yields a very shallow minimum. Therefore, if the thrust or exit diameter requires an increase in p_c the penalty paid in additional casing weight will be small.

D. TYPICAL PROPELLANTS

From the preceding discussion it can be seen that some knowledge of propellants to be used in the rocket motor is needed. The thrust developed by a rocket motor depends directly upon the pressure in the chamber.

$$T = C_F\ A_T\ P_C$$

Since

$$W_p = \frac{I}{I_{sp}} = \frac{Tt_b}{I_{sp}}$$

$$\frac{dW_c}{dp_c} + (W_c + W_N)\ \frac{I_{sp}}{I_{sp}^{\ 2}}\ \frac{dI_{sp}}{dp_c} - \frac{W_M}{I_{sp}}\ \frac{dI_{sp}}{dp_c} = 0$$

From equation (8)

$$W_c + W_N = W_M - W_p$$

Substituting for $W_c + W_N$

$$\frac{dW_c}{dp_c} - \frac{W_p}{I_{sp}}\ \frac{dI_{sp}}{dp_c} = 0$$

From equation (6)

$$\frac{dW_c}{dp_c} = \frac{2.4\pi r^2 \ell_c \rho_c}{\sigma_y} \tag{11}$$

Since

$$W_p = \pi r^2 \ell_c \rho_p$$

$$\frac{dW_c}{dp_c} = \frac{2.4\pi\rho_c\ W_p}{\rho_p\ \sigma_y} \tag{12}$$

from equation (3)

$$\frac{dI_{sp}}{dp_c} = \frac{RT_o}{g_c p_c I_{sp}}\ \left(\frac{p_o}{p_c}\right)^{\frac{\gamma-1}{\gamma}} \tag{13}$$

Because of this relationship, high pressures are needed for the boost phase, and relatively low pressure are needed for the sustain phase of flight. The pressure developed in a rocket motor chamber is a function of the burn rate and burn surface area of the propellant. In order to provide more burn area for the boost phase, the grain normally has an internal star perforation; while a sustain motor is normally an end burning grain of solid cross-section. The volumetric loading of a rocket motor is defined as the ratio of the propellant volume to the rocket motor chamber volume.

$$\eta_p = \frac{\text{Grain volume}}{\text{Chamber volume}}$$

Due to erosive burning effects the volumetric loading of a booster is normally limited to less than 0.9. For efficient packing the ratio varies from 0.7 to 0.9. The volumetric loading of an end burning sustainer engine is normally 1.0. The range of propellant characteristics is shown in Table (8-I).

TABLE (8-I). Typical Propellant Properties [14,15].

	Sustainer	Booster
I_{sp} (sec)	180-210	210-260
ρ_p (lbm/in^3)	.059-.062	.062-.065
γ	1.24 - 1.27	1.22 - 1.26
η_p	1.00	0.85

E. DESIGN EXAMPLE (BOOSTER)

From the previous analysis the launch speed is M = 1.5, and the cruise speed is M = 3.0 at an altitude of 10,000 feet. The boost incremental velocity is then,

$$\Delta V_B = 1616.10 \text{ ft/sec}$$

If the maximum acceleration during boost is a constant 30 g's (assume sea level g_c), the time of burn is,

$$t_b = \Delta V_B / a_{max} = \frac{1616.10 \text{ ft/sec}}{30(32.2 \text{ ft/sec}^2)}$$

$$t_b = 1.67 \text{ sec}$$

From equation (4) with $\gamma_L = 0$

$$\ell_n \frac{W_L}{W_E} = \frac{\Delta V_B}{g\, I_{sp}}$$

Assume I_{sp} = 250 sec from Table (I)

$$\ell_n \frac{W_L}{W_E} = 0.2008$$

$$W_p = W_L \left(1 - \frac{W_E}{W_L}\right)$$

For $W_L = 794.83$

$$W_p = 144.57 \text{ } \ell\text{bm}$$

The thrust provided is

$$(T)_b = \frac{I_{sp}\ W_p}{t_b} = 21{,}642\ \ell b_f$$

Since the missile flies essentially at zero angle of attack during boost, the drag at the end of boost is,

$$D = (C_{D_0})\ q\ S_{ref}$$

$$D = 2006\ \ell b_f$$

Therefore if an average drag of 1000 lbs is assumed, equation (3) can be used to find a new W_L/W_E

$$\ell n\ \frac{W_L}{W_E} = \frac{\Delta V_B\ W_p}{g(T - D)t_b}$$

$$\frac{W_L}{W_E} = .2270$$

$$W_p = 161.40\ \ell b_m$$

This gives a thrust of 24,162 lbs. One more iteration of equation (4) gives,

$$W_p = 159.46\ \ell b_m$$

$$(T)_s = 23{,}872\ \ell b_f$$

Continued iteration of equation (4) does not change the propellant weight.

From Table (I); $\rho_p = .062\ \ell b_m/in^3$

$$\eta_p = .85$$

The booster volume then becomes

$$V_B = 3025.81\ in^3$$

Allowing one-half inch for structure, the booster length becomes.

$$L_B = \frac{4\ V_B}{\pi D_c^{\ 2}} = 42.69\ \text{inches}$$

F. DESIGN EXAMPLE (SUSTAINER)

The maximum range of the missile was determined to be 35 nmiles.

$$R_{max} = 212{,}800\ ft$$

The distance traveled during boost is

$$S_B = \bar{V}_M\ t_b$$

$$\bar{V} = \frac{V_1 + V_2}{2} = 2424.15\ ft/sec$$

$$S_B = 4048.33\ ft$$

Therefore, at a cruise Mach number of 3.0, the sustainer time of burn is

$$t_s = 64.59\ sec.$$

The cruise drag consists of zero-lift drag and induced drag. The lift coefficient of the missile minus the booster is;

$$C_L = \frac{W}{q\, S_{ref}}$$

$$C_L = 0.1270$$

From Chapter 6

$$C_D = C_{D_0} + C_L{}^2/C_{N\alpha}$$

$$C_D = .4016$$

The cruise drag then becomes

$$D = 2009\ \ell b_f$$

The total impulse required is then;

$$(I_T)_s = Dt_s = 129{,}761\ \ell b_f - \text{sec}$$

From Table (I) the specific impulse is 210 sec; therefore, the weight of propellant needed for cruise is

$$(W_p)_s = \frac{(I_T)_s}{I_{sp}} = 618\ \ell b_m$$

The volume required is

$$V_s = 9967.7\ \text{in}^3$$

The sustainer length becomes,

$$L_s = \frac{4V_s}{\pi D_c^2} = 140.62 \text{ inches}$$

The total rocket motor length is, L_{RM};

$$L_{RM} = L_B + L_S$$

$$L_{RM} = 183.31 \text{ in}$$

The rocket motor alone exeeds the total length of the baseline missile. This will lead to large length to diameter ratios for the entire missile; therefore, the rocket motor length must be decreased. That is the subject of the next section.

G. REDUCING ROCKET MOTOR LENGTH

If the rocket motor length of the last section leads to excessive length to diameter ratios for the missile, the motor length must be decreased. This may be accomplished in one of two ways: (1) If the mission profile has a long cruise segment, the cruise altitude may be increased thereby decreasing the drag and the total impulse required. (2) If the cruise altitude cannot be varied, the missile diameter must be resized for propulsion considerations. In this design example option (2) will be selected.

The missile length can be expressed as

$$L = L_n + L_G + L_c + L_{WH} + L_{RM} \tag{15}$$

L_n = Nose length

L_G = Guidance section length

L_c = Control section length

L_{WH} = Warhead section length

L_{RM} = Rocket motor length

The nose and warhead sections have been previously defined. Since the propellant weight for the range requirement is known, the diameter necessary can be determined if a maximum missile length is specified. The drag will increase slightly due to the increased diameter but the total impulse, and therefore the propellant weight, will change only slightly.

The rocket motor length can be expressed in terms of the diameter by

$$L_{RM} = \frac{4W_p}{\rho_p \pi D^2}$$

Equation (15) then becomes

$$(L) = L_n + L_G + L_c + L_{WH} + \frac{4Wp_c}{\rho_p \pi D^2}$$

The guidance and the control sections are each normally about 10 percent of the missile length.

$$(L) = (\frac{L_n}{D})D + .1L + .1L + (\frac{L_{WH}}{D})\ D + \frac{4W_p}{\rho_p \pi D^2}$$

$$\left[\frac{L_n}{D} + \frac{L_{WH}}{D}\right] D^3 - .8LD^2 + \frac{4W_p}{\rho_p \pi} = 0 \qquad (16)$$

As mentioned in Chapter 2 the missile is normally designed for an existing launcher. This launcher will have a maximum length that it can accomodate, L_{max}. If this value is substituted into equation (16), the required diameter can be found.

1. Design Example (Resizing for Propulsion)

From previous analysis; $L_n/D = 2.23$

$$L_{WH}/D = 2.50$$

The propellant weight from before was, $W_p = 777.46$ lbs. If the maximum length of the missile is taken as 210 inches, equation (16) becomes,

$$4.73D^3 - 168D^2 + 15{,}467.08 = 0.0$$

The required diameter is then,

$$(D)_{req} = 11.75 \text{ inches}$$

Allowing 0.25 in for structure, the missile diameter becomes 12 inches. From the equations for the rocket motor lengths,

$$L_b = 26.62 \text{ in}$$

$$L_s = 90.47 \text{ in}$$

$$L_{RM} = 117.09 \text{ in}$$

H. DESIGN EXAMPLE (CHAMBER PRESSURE)

From equation (14), the strength to density ratio can be solved for in terms of p_c.

$$\left(\frac{\sigma_y}{\rho_c}\right)_{min} = \frac{2\gamma}{(\gamma-1)} \left[\left(\frac{p_o}{p_c}\right)^{\frac{1-\gamma}{\gamma}} -1 \right] p_c \left(\frac{2.4}{\rho_p}\right)$$

If the minimum usable chamber pressure is P_c = 500 psi, and using the propellant previously selected.

$$\gamma = 1.24$$

$$\rho_p = .062$$

$$p_0 = 10.11$$

the minimum strength to density required can be found.

$$\left(\frac{\sigma_y}{\rho_c}\right)_{min} = 225{,}542.87 \text{ in}$$

Inconnel 718 is a common metal used in combustion chambers and has the following properties [4]:

$$\sigma_y = 180{,}000 \text{ psi}$$

$$\rho_c = .2662 \ b_m/in^3$$

$$\frac{\sigma_y}{\rho_c} = 676{,}183 > \left(\frac{\sigma_y}{\rho_c}\right)_{min}$$

The optimum chamber pressure is then from equation (14)

$$p_c = 1132.55 \text{ psi}$$

The rocket motor chamber wall thickness is given by equation (5) as

$$t = \frac{p_{max}\ r}{\sigma_y}$$

$$t = 0.05 \text{ inches}$$

The wall weight is given by equation (2)

$$W_c = 2\pi\ r\ell_{RM} t\rho_c$$

$$W_c = 59.5\ \ell b_m$$

I. DESIGN EXAMPLE (SIZING THE NOZZLE)

For initial analysis it is assumed that the flow is fully expanded, in a nozzle with a half angle of 15 degrees. With the chamber pressure of 1132.55 psi the thrust coefficient at altitude is

$$C_{F_d} = C_d \lambda \sqrt{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1 - \left(\frac{p_0}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$C_{F_d} = 2.3023$$

The throat area and diameter then become

$$A_t = \frac{T}{C_{F_d}} p_c = 9.1552 \text{ in}^2$$

$$d_t = 3.4142 \text{ in}$$

From isentropic tables for $p_0/p_c = .0089$

$$\frac{d_t}{d_e} = \left(\frac{A^*}{A}\right)^{1/2} = .3342$$

The exit diameter becomes,

$$d_e = 10.22 \text{ in}$$

The nozzle length for a 15 degree half angle is,

$$\ell_n = 12.70 \text{ in}$$

The nozzle is shown in Figure (8-2). Figure (8-3) is the design with resized diameter and length for propulsion and the optimum wings determined in Chapter 7.

J. TAIL SIZING

As mentioned in Chapter 7 the tail (canard) sizing is accomplished for zero static stability at launch. Now that the missile length has been fixed, the canard can be sized. Figure (8-3) is a drawing of the design to this point. The total lifting surface required is

$$S_W + S_c = 6.57 \text{ ft}^2$$

if

$$k = S_c/S_W \tag{16}$$

From equation (5) in Chapter 7, for $C_{M\alpha} = 0$

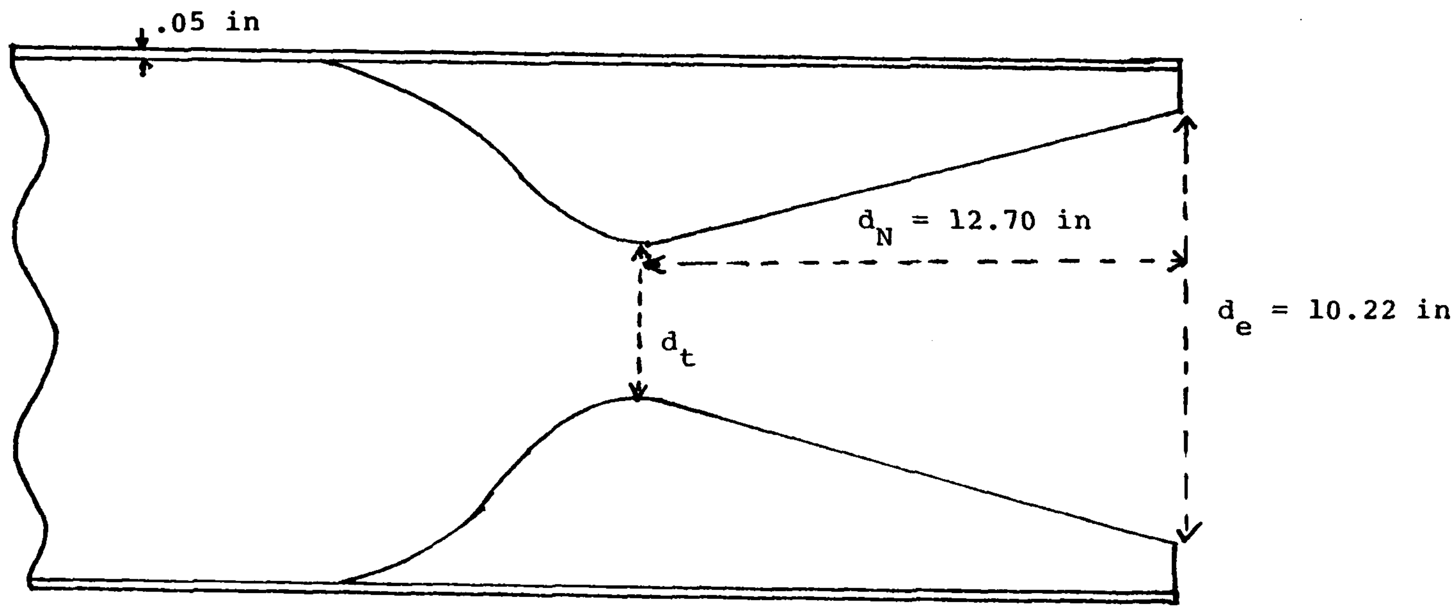


Figure (8-2). Nozzle geometry.

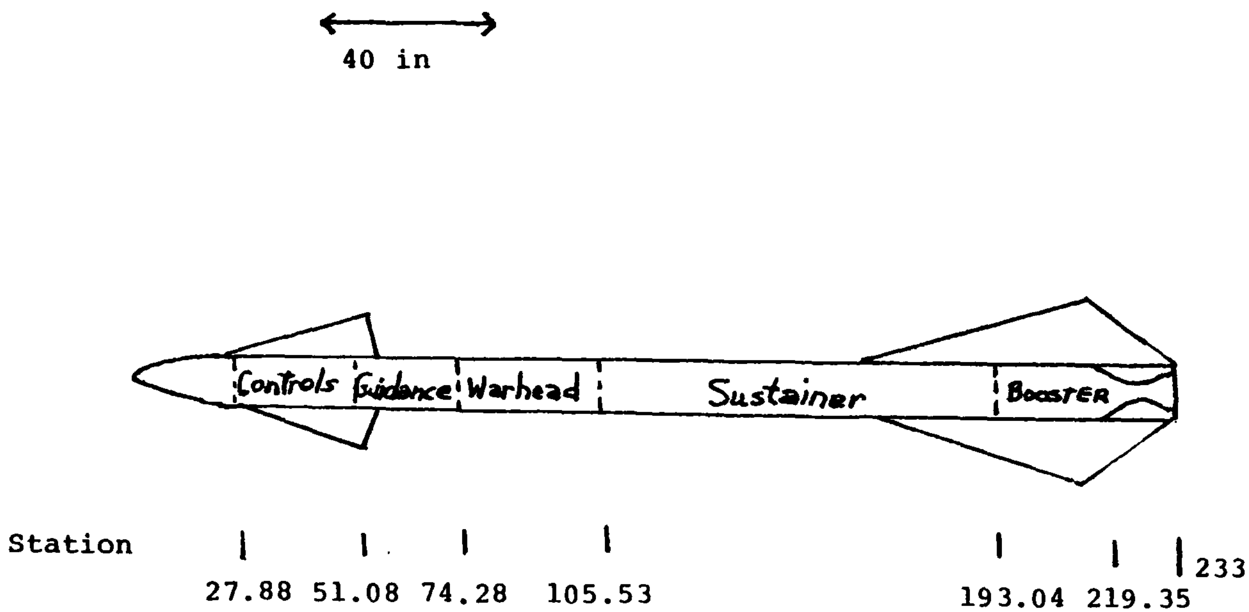


Figure (8-3). Missile design.

$$0 = (C_{N\alpha})_N + (C_{N\alpha})_W \, x_W \frac{S_W}{S_{ref}} (K_{W(B)} + K_{B(W)})$$

$$+ (C_{N\alpha})_C \, x_C \frac{S_W}{S_{ref}} (K_{C(B)} + K_{B(C)}) \tag{17}$$

Equations (16) and (17) above can be solved for S_W and k.

$$S_W = 4.70 \text{ ft}^2$$

$$k = 0.40$$

Therefore, $S_c = 1.87$

If the same aspect ratio as found in Chapter 7 is used, the wing and canard planforms become,

Wing: $b_w = 1.86$ ft Canard: $b_c = 1.36$ ft

$(c_r)_w = 5.05$ ft $(c_r)_c = 2.75$ ft

$(c)_w = 3.60$ ft $(c)_c = 2.63$ ft

IX. NONLINEAR AERODYNAMICS AND AERO1

As mentioned in Chpater 5 the analysis thus far has been for one speed and small angles of attack. The aerodynamics change dramatically from subsonic to supersonic flow and with increasing angle of attack. This chapter presents the methods used primarily by USAF Stability and Control DATCOM and covers all configurations and flight speeds. As will be shown, the method becomes very involved and therefore lends itself to programming on a digital computer.

The lifting characteristics of both wings and bodies become nonlinear as the missile angle of attack increases above 10°. Up to this point in the thesis development only the linear contribution has been considered. For large angles of attack, the nonlinear term, which is due to flow separation, must be considered. The relative effect of these terms on the normal force and pitching moment coefficients is shown in Figure (9-1).

A. VISCOUS CROSS-FLOW

As can be seen in Figure (9-1), at large angles of attack the forces acting are primarily nonlinear. The nonlinear term is normally described through the use of the viscous cross-flow coefficient, C_{d_c} .

$$C_{d_c} = \frac{f_v}{q_n \, S_p} \qquad S_p = \text{planform area.}$$

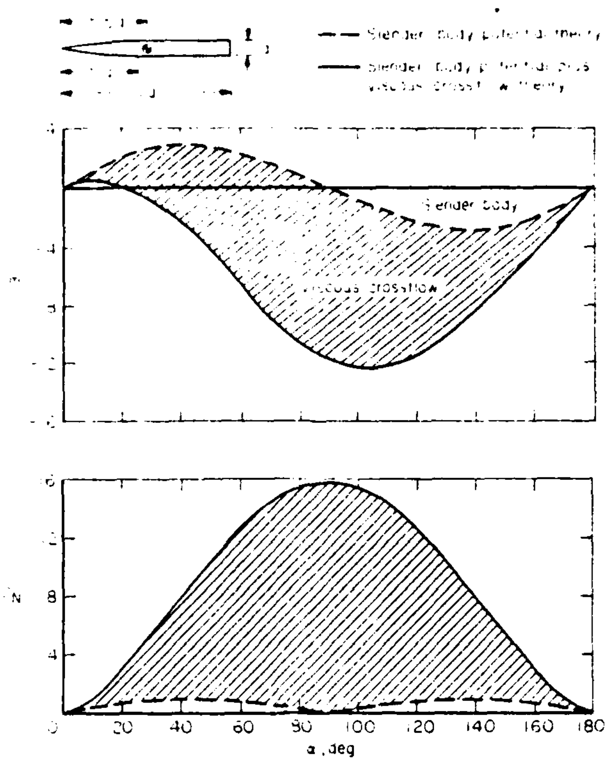


Figure (9-1). Relative contributions of linear and nonlinear terms [19].

For an infinitely long circular cylinder, the viscous cross-flow force per unit length is

$$f_v = 2r\, C_{d_c}\, q_n \tag{1}$$

The viscous cross-flow coefficient is determined experimentally and is a function of normal Mach number and Reynolds number. Figure (9-2) gives the cross-flow drag coefficient as a function of cross-flow Mach number.

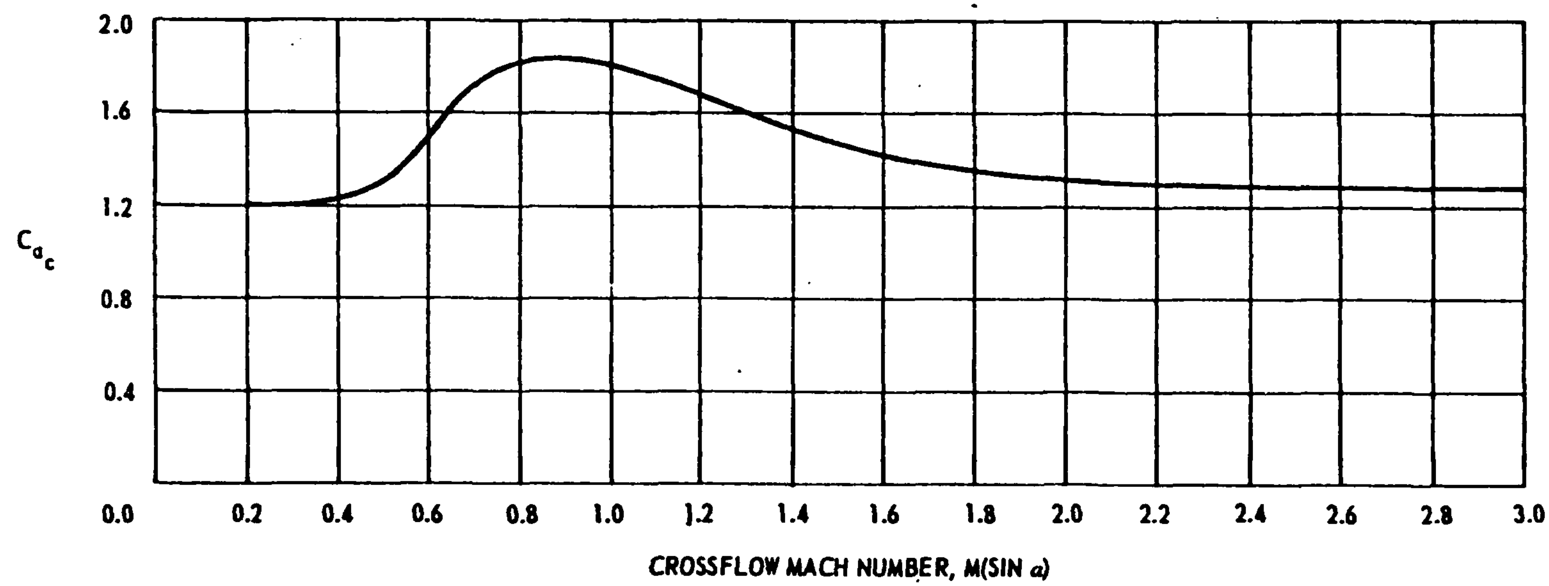


Figure (9-2). Cross-flow drag coefficient [18].

$$M_n = M_M \sin\alpha$$

$$R_{e_n} = R_e \sin\alpha$$

$$V_n = V_M \sin\alpha$$

Since in real flow there is spillage around the ends of a finite length cylinder, the drag is less than that for an infinite, 2-D cylinder. The cross-flow drag proportionality constant, n, is the ratio of the drag coefficient of a finite cylinder to the drag coefficient of an infinite cylinder.

$$n = \frac{C_{d_c}}{(C_{d_c})_{2\text{-}D}}$$

The proportionality constant is also determined experimentally and is given in Figure (9-3). Notice that the cross-flow drag proportionality constant approaches one as the length to diameter ratio becomes large, or the 2-D situation is approached.

The viscous cross-flow force per unit length for a finite cylinder then becomes

$$f_v = 2rnC_{d_c} \frac{\rho V_n^{\,2}}{2} \tag{2}$$

Since

$$\frac{\rho V_n^{\,2}}{2} = \frac{\rho V_M^{\,2}}{2} \sin^2\alpha = q \sin^2\alpha$$

equation (2) becomes,

$$f_v = 2nC_{d_c} q\, r \sin^2\alpha$$

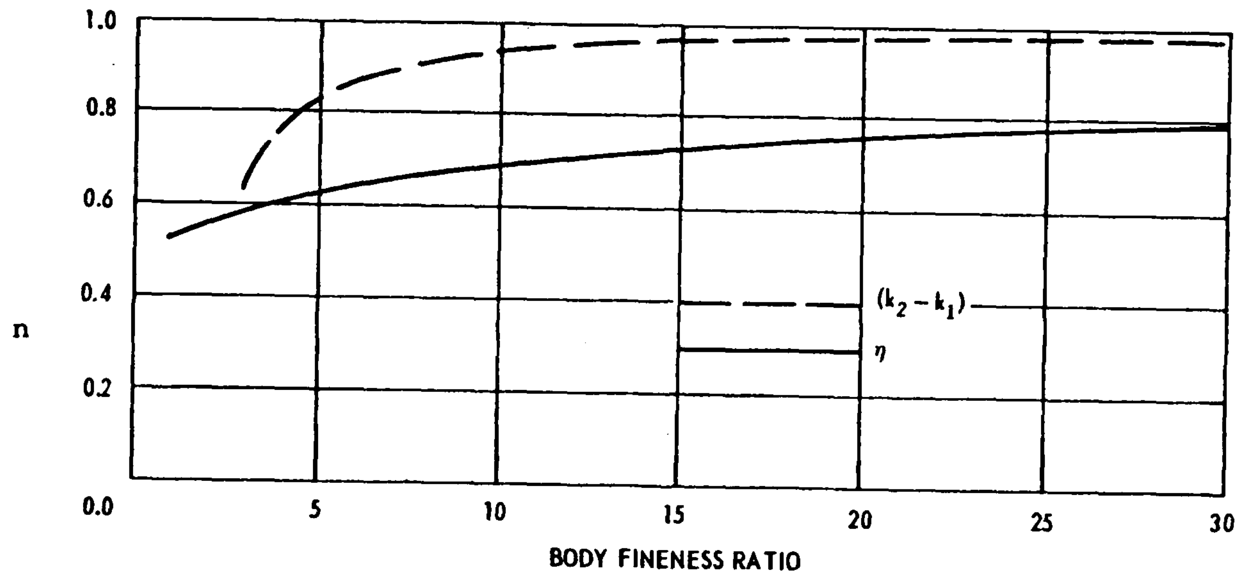


Figure (9-3). Cross-flow drag proportionality constant.

The viscous contribution to the normal force acting on the cylinder then becomes

$$(C_N)_V \equiv \frac{F_v}{q\, S_{ref}} = \frac{2nC_{d_c} \sin^2\alpha}{S_{ref}} \int_0^{\ell} r dx$$

For a uniform cylinder,

$$(C_N)_V = n\, C_{d_c} \frac{S_p}{S_{ref}} \sin^2\alpha$$

If this force is added to the term predicted by slender body potential theory, the total normal force acting on the body can be found. Reference [19] gives this total force as;

$$(C_N)_B = \frac{S_b}{S_{ref}} \sin^2\alpha \cos\frac{\alpha}{2} + n\, C_{d_c} \frac{S_p}{S_{ref}} \sin^2\alpha$$

Similar terms can be developed for the wing and tail since they also exhibit nonlinear behavior at high angles of attack. Care must be taken to separate the lift of Chapter 5 into the lift acting on the wing panel and the additional lift on the body before the cross-flow term is applied. The nonlinear cross-flow component of wing lift is caused by flow separation and the formation of vortices on the upper surface of the wing. This viscous term is given by, $C_{N_{W(V)}}$.

$$C_{N_{W(V)}} = C_{d_n} \sin^2\alpha \frac{S_W}{S_{ref}}$$

Where C_{d_n} is the cross-flow drag coefficient for a flat plate and is given in Figure (9-4).

B. TOTAL MISSILE LIFT

The remainder of this chapter is a summary of references [17] and [18]. With the addition of the force due to viscous cross-flow, the total lift on the body becomes

$$C_{N_B} = (C_N)_B + C_{N_{B(W)}} + C_{N_{B(T)-\alpha}} + C_{N_{B(T)-\delta}}$$

where,

$(C_N)_B$ = linear and nonlinear lift force on the body

$C_{N_{B(W)}}$ = additional lift on the body due to the wing

$C_{N_{B(T)-\alpha}}$ = additional lift on the body due to the tail (due to angle of attack)

$C_{N_{B(T)-\delta}}$ = additional lift on the body due to the tail (due to control deflection)

The additional lift on the body in the presence of the wing and tail can be found as described in Chapter 6.

The wing lift is now composed of a linear and a nonlinear component and becomes

$$C_{N_W} = C_{N_{W(B)}} + C_{N_{W(V)}}$$

$$C_{N_W} = K_{W(B)} \ (C_{N_\alpha})_W \frac{S_W}{S_{ref}} \sin\alpha + C_{d_n} \sin^2\alpha \frac{S_W}{S_{ref}}$$

The tail lift is found in a similar manner only with the additional term for any control surface deflection, δ.

$$C_{N_T} = C_{N_{T(B)-\alpha}} + C_{N_{T(B)-\delta}} + C_{N_{T(V)}}$$

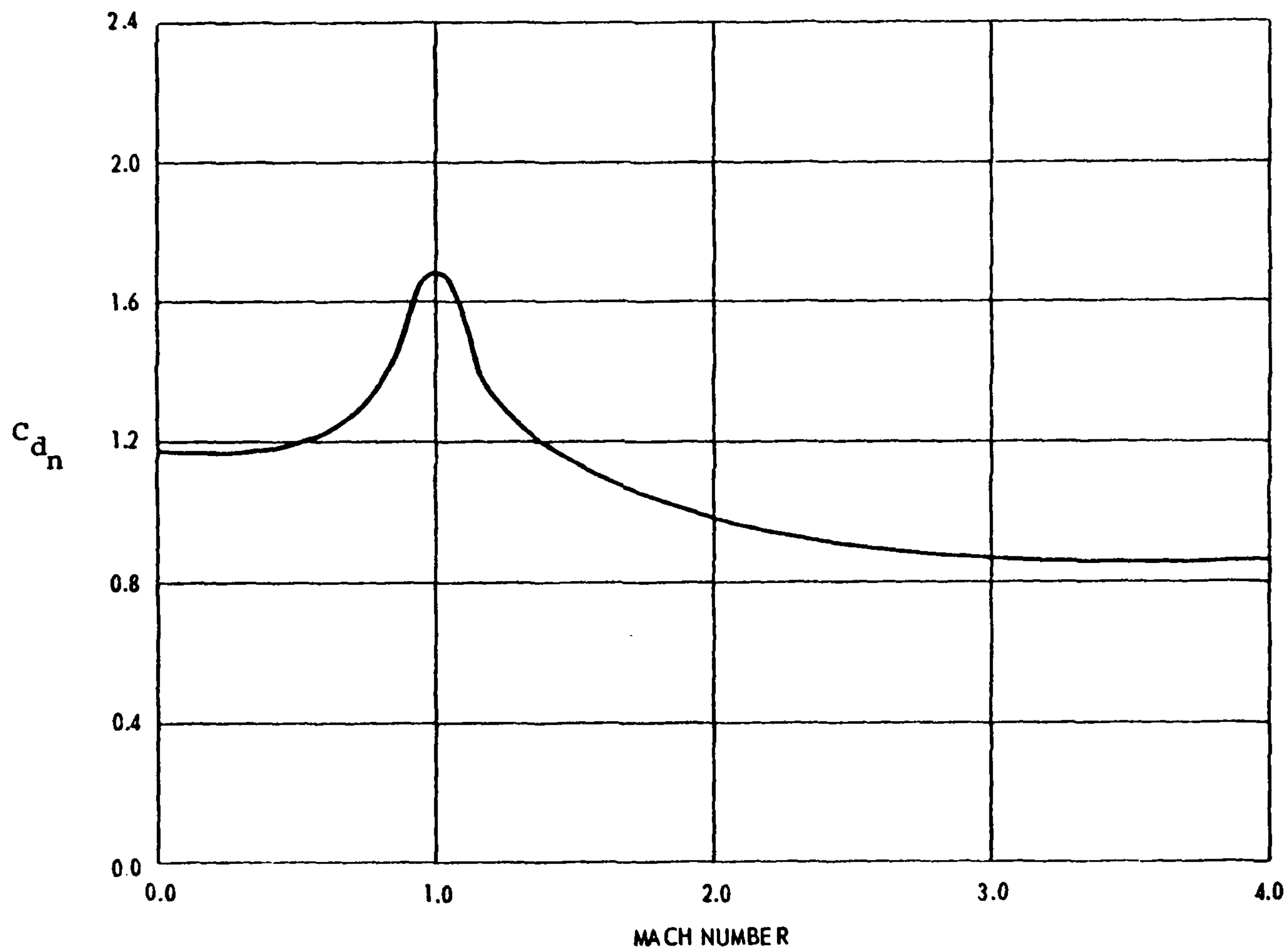


Figure (9-4). Drag coefficient for a flat plate normal to flow [18].

Notice that the linear terms in the above equations are multiplied by $\sin\alpha$ instead of α as in Chapter 6. The linear theory from which the Chapter 6 equations were derived assumes small angles of attack and therefore $\sin\alpha \approx \alpha$. This is not true at higher angles of attack and is therefore included here.

The total normal force then becomes, C_N

$$C_N = C_{N_B} + C_{N_W} + C_{N_T} + C_{L_i} \quad .$$

The last term, C_{L_i}, is the lift-loss due to downwash and is given by

$$C_{L_i} = \frac{(C_{L\alpha})_W (C_{L\alpha})_T \left[K_{W(B)} \sin\alpha + k_{W(B)} \sin\delta\right] i \, (b - r)_T \, S_W}{2\pi \, AR_T \, (f_w - r_w) \, S_{ref}}$$

where,
i = interference factor

f_w = votex location

the above terms are found by the methods of reference [13].

C. DRAG CHARACTERISTICS OF A MISSILE

The total drag acting on a missile is the sum of the zero-lift drag and the induced drag (due to angle of attack and/or control surface deflection). The zero lift drag of bodies and wings is highly dependent on the missile speed.

Three speed regimes are normally considered.

$$\text{Subsonic} \longrightarrow 0 \leq M_M < .8$$

$$\text{Transonic} \longrightarrow .8 \leq M_M \leq 1.2$$

$$\text{Supersonic} \longrightarrow M > 1.2$$

Because of the empirical nature of the formulas for zero-lift drag, the procedures followed are essentially those of DATCOM [16].

1. Zero Lift Drag

a. Subsonic

At subsonic speeds the zero-lift drag consists of skin friction (incompressible) and pressure drag. The pressure drag at subsonic speeds is usually small compared to the drag due to skin friction. The entire zero-lift drag of a missile at subsonic speeds is given by;

$$C_{D_0} = C_{D_{0B}} + C_{D_{0W}} + C_{D_{0T}}$$

Where the components are the body, wing and tail contributions.

(1) Body drag, $C_{D_{0B}}$. The body zero-lift drag is given by;

$$C_{D_{0B}} = 1.02\, C_{f_B} \left[1 + \frac{1.5}{f^{3/2}} + \frac{7}{f^3} \right] \frac{(S_{Wet})_B}{S_{ref}} + C_{A_B}$$

where C_{A_B} is found by the methods of Chapter 5.

The first term is the skin friction contribution and the next two terms are the pressure contributions. f is the body fineness ratio and is given by;

$$f = \frac{L}{D}$$

(2) Wing drag, $C_{D_{0W}}$. The wing zero-lift drag is given by,

$$C_{D_{0W}} = C_{f_W} \left[1 + 2\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4\right] \frac{(S_{Wet})_W}{S_{ref}}$$

$(S_{Wet})_W$ is the entire wetted area of the wings. The thickness to chord ratio is given by (t/c).

(3) Tail drag, $C_{D_{0T}}$. The tail zero-lift drag is given by,

$$C_{D_{0T}} = C_{f_T} \left[1 + 2\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4\right] \frac{(S_{Wet})_T}{S_{ref}}$$

The above analysis assumes fully turbulent flow along all surfaces. C_{f_B}, C_{f_W} and C_{f_T} are the local average skin friction coefficients based on the local Reynolds number, R_e.

The reference lengths are the body length and wing/tail mean aerodynamic chords. The skin friction coefficient is then given by

$$C_f = \frac{4.55}{(\log_{10} R_e)^{2.58}}$$

b. Transonic

The total transonic zero-lift drag is composed of skin-friction drag, transonic wave drag, pressure drag and base pressure drag. The compressible skin friction drag is found by using a correction factor on the incompressible coefficient, C_{f_B}, found for subsonic flow. The compressibility correction is found by the methods of Chapter 6. The skin friction drag then becomes

$$C_{D_{fB}} = 1.02\, C_{f_c} \frac{(S_{Wet})_B}{S_{ref}}$$

The subsonic pressure drag is the same as before

$$C_{D_{pB}} = 1.02\, C_{f_B} \left[\frac{1.5}{f^{3/2}} + \frac{7}{f^3} \right] \frac{(S_{Wet})_B}{S_{ref}}$$

The above equation applies for Mach numbers in the range of .8 to 1.0. The pressure drag then decreases linearly to zero at a Mach number of 1.2. The transonic wave drag $C_{D_{rB}}$ is determined using Figure (9-5), which is a function of nose fineness ratio $L_{N/D}$.

The total transonic zero-lift drag of the body then becomes

$$C_{D_{0B}} = C_{D_f} + C_{DpB} + C_{D_{VB}} \frac{S_N}{S_{ref}} + C_{A_B}$$

where S_N is the cross sectional area at the nose-body junction.

The total transonic zero-lift drag of the aerodynamic surfaces is composed of the skin friction drag and a drag increment, ΔC_{D_0}, which is the transonic wave drag.

Experimental results show little increase in the viscous drag of aerodynamic surfaces from the subsonic to the transonic regimes; therefore the skin friction and pressure drag is the same as for subsonic flow and is given by

$$C_{D_{0W}} = C_{f_w} \left[1 + 2(\frac{t}{c}) + 100(\frac{t}{c})^4\right] \frac{S_{Wet}}{S_{ref}}$$

The wave drag of the aerodynamic surfaces if found from Figure (9-6) and is a function of $\frac{t}{c}$, AR and M. For swept wings the Mach number used in Figure (9-6) is given by,

$$M' = M \, [\cos \Delta \, c/4]^{1/2}$$

The transonic wave drag increment is then given by

$$\Delta C_{D_{0W}} = \Delta C_{D_{0W}}' \, [\cos \Delta \, c/4]^{2.5} \, \frac{S_W}{S_{ref}}$$

where $\Delta C_{D_{0W}}'$ is obtained from Figure (9-6). The tail zero-lift drag is found in the same manner as the wing. The total zero-lift drag (transonic) is then given by;

$$C_{D_0} = C_{D_{0B}} + C_{D_{0W}} + \Delta C_{D_{0W}} + C_{D_{0T}} + \Delta C_{D_{0T}}$$

c. Supersonic

The supersonic zero-lift drag of a missile is determined empirically by assuming a parabolic variation of C_{D_0} with Mach number between 1.2 and 3.0. The resulting equation is for the entire missile and is given by

$$C_{D_0} = C_{D_0}' - 1.7209 \, (C_{D_0}'' - C_{D_0}') + 1.5708 \, (C_{D_0}'' - C_{D_0}') \sqrt{M}$$

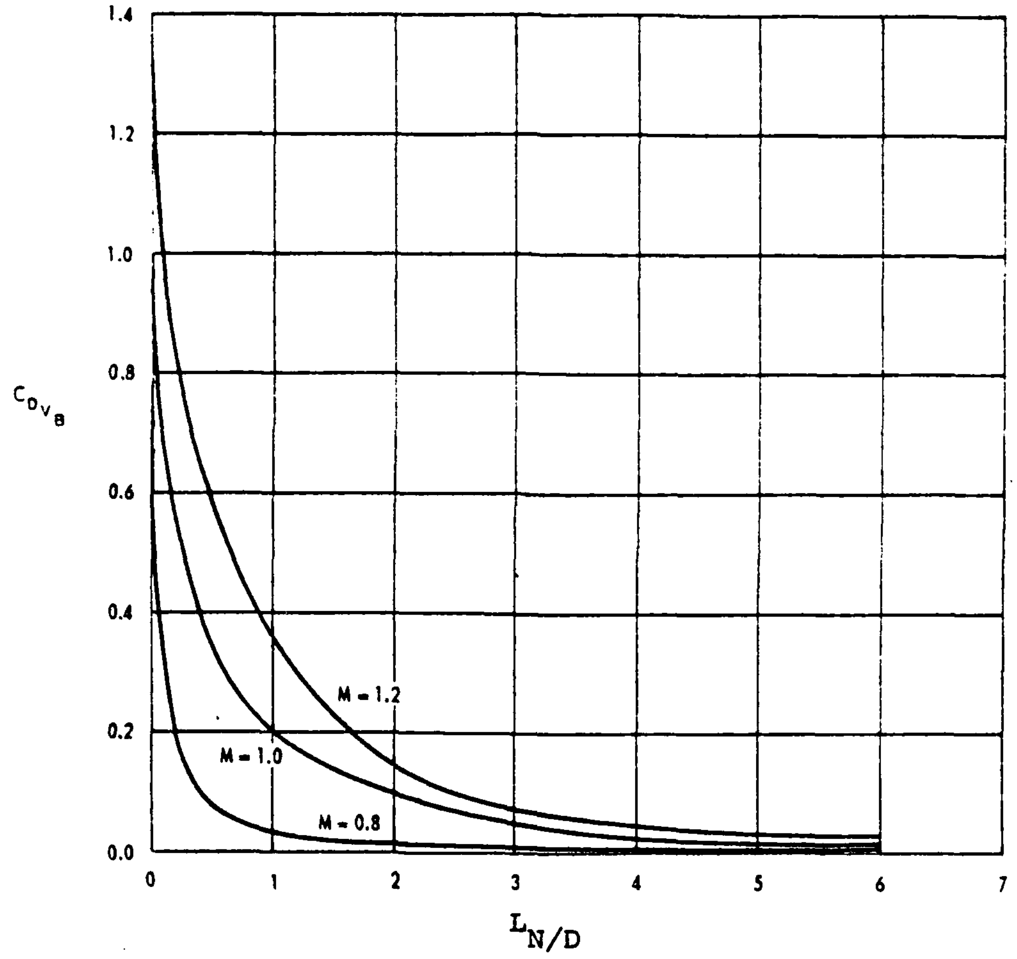


Figure (9-5). Transonic wave drag for ogival and blunted conical forebodies [18].

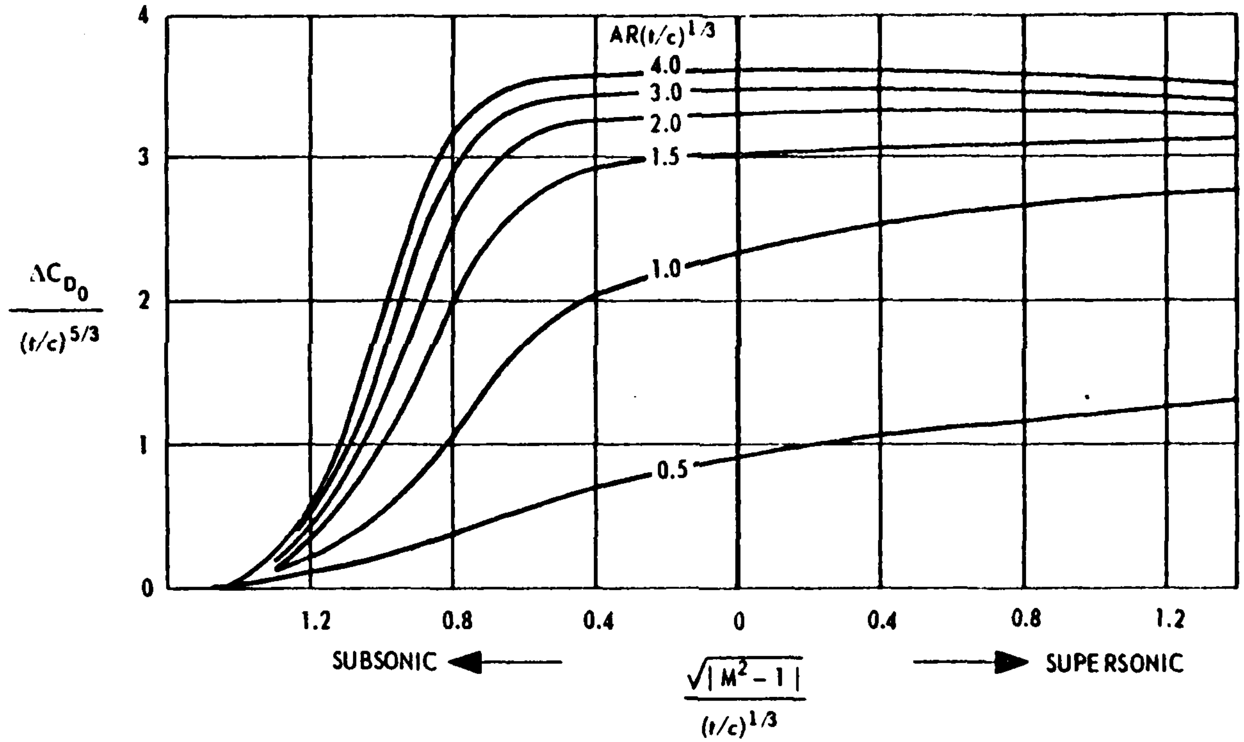


Figure (9-6). Transonic C_{D_0} for unswept wings [18].

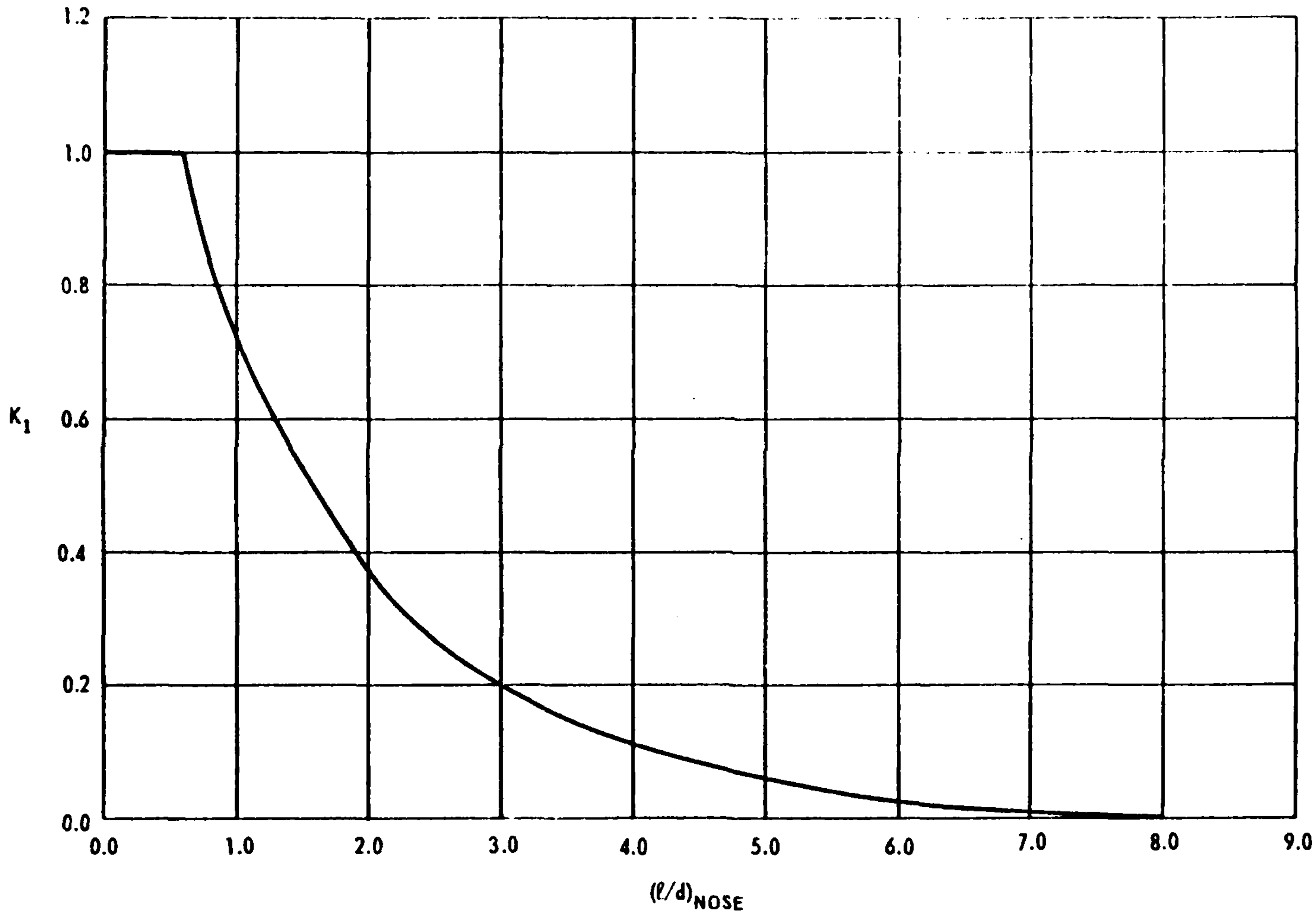


Figure (9-7). Ratio of C_{D_W} for various L/D to C_{D_W} hemispherical [18].

where

$$C_{D_0}' = (C_{D_0})_{M = 1.2}$$

$$C_{D_0}'' = (C_{D_0})_{M = 3.0}$$

C_{D_0}' is determined by using the methods for transonic flow.

The magnitude of the supersonic wave drag is highly dependent upon the nose shape. For this reason two methods are used to determine C_{D_0}'' .

<u>Method I</u>: This method is for blunted ogives, pointed ogives and blunted cones. In this method

For $L_{N/D} \leq .5$ $\qquad C_{D_0}'' = C_{D_0}'$

For $L_{N/D} \geq 8.0$ $\qquad C_{D_0}'' = (C_{D_0})_{M = .8} + \Delta C_{D_{0W}} + \Delta C_{D_{0T}} + C_{A_B}$

The above values are determined from the methods of transonic flow.

For $L_{N/D} = .5$ to 8.0

$$C_{D_0}'' = K_1 \, C_{D_0}'$$

K_1 in the above equation is derived empirically and is given in Figure (9-7).

<u>Method II</u>: This method is for pointed conical noses. In this method C_{D_0}'' is determined by

$$C_{D_0}'' = (C_{D_0})_{M = .8} + \Delta C_{D_{0W}} + \Delta C_{D_{0T}} + (C_{D_{VN}})_{M = 3} + C_{A_B}$$

The first three terms in the above equation are found by transonic flow methods. The forebody wave drag, $C_{D_{VN}}$, for M = 3.0 is found using Figure (9-8). The nose semi-vertex angle, θ_N, is the same as σ in Chapter 6. In all flow regimes the base pressure drag is found as in Chapter 6.

2. Induced Drag

The induced drag due to angle of attack depends upon the flight regime the missile is in. For $M < .85$ and $AR > 3.0$ the induced drag is,

$$C_{D_i} = \frac{(C_L)^2}{\pi ARe}$$

where e is the Oswald efficiency factor $\doteq 0.7$.
The tactical missile normally has an aspect ratio of less than 3.0. For all flight speeds with $AR < 3.0$ the induced drag is

$$C_{D_i} = C_L \tan \alpha$$

The component induced drag coefficients are found in the same manner as above using component lift coefficients.

3. Total Drag

From the zero-lift drag and induced drag the missile total drag becomes,

$$C_D = C_{D_0} + C_{D_i}$$

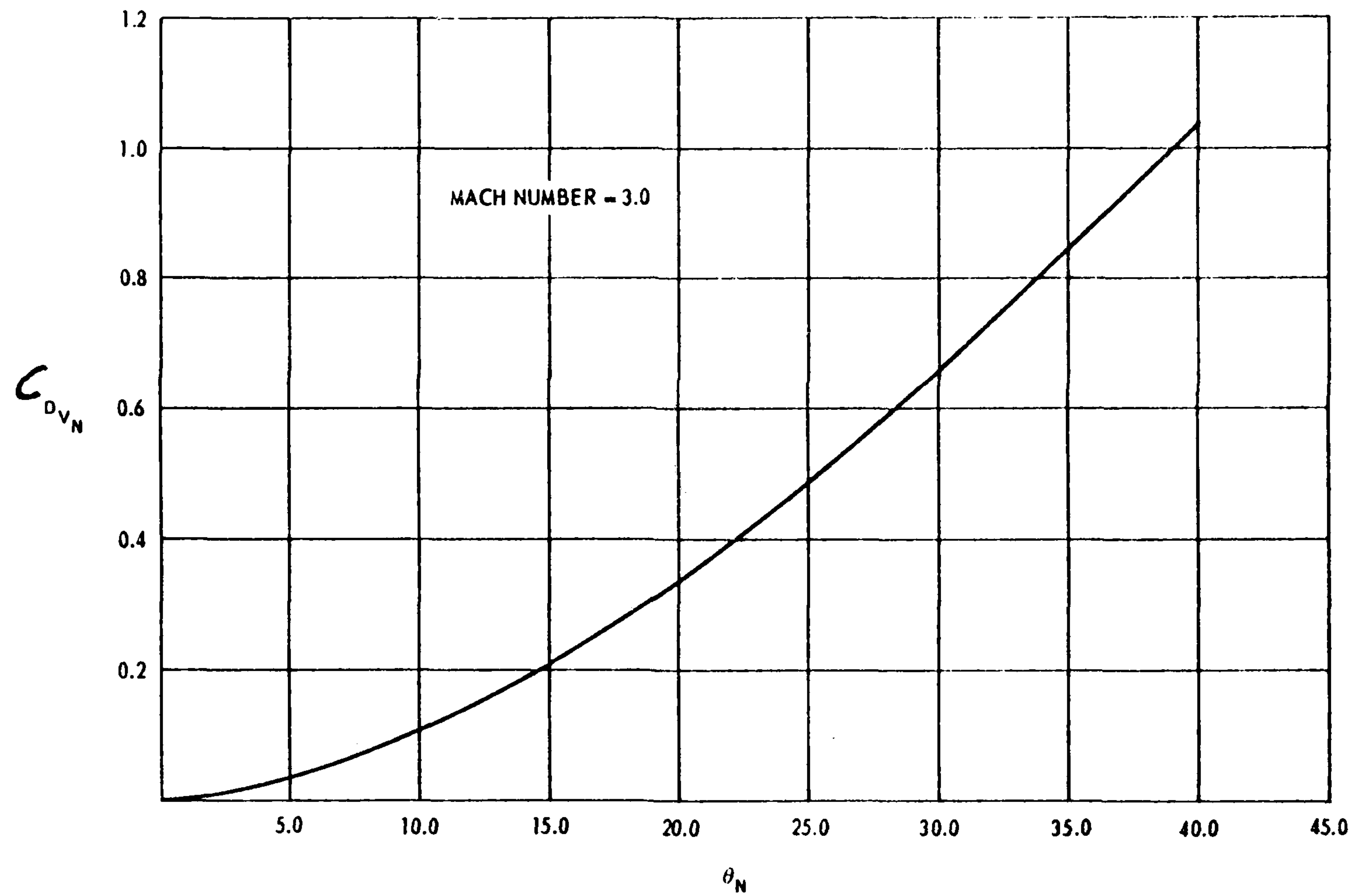


Figure (9-8). Wave drag of pointed conical nose [18].

D. PITCHING MOMENT CHARACTERISTICS

The pitching moment of a missile is equal to the sum of the pitching moments due to lift and drag forces acting on the body, wings and tails. If only small angles of attack are of interest, the pitching moment is due primarily to the lift forces. The methods presented here are for all angles of attack.

1. Body

The body alone pitching moment about its center of gravity is given from slender body theory and viscous cross-flow theory as

$$C_{M_B} = \left[\frac{V_B - S_B(L - x_{cG})}{S_{ref} \, L_{ref}} \right] \sin^2\alpha \cos\frac{\alpha}{2} + n \, C_{d_c} \left(\frac{S_p}{S_{ref}}\right) \left(\frac{x_{cG} - x_p}{L_{ref}}\right) \sin^2\alpha$$

S_p = Planform area

x_p = Centroid of planform area

V_B = Body volume

S_B = Base area

With C_{M_B} given the center of pressure of the body becomes

$$(x_{c_p})_B = \left(\frac{x_{cG}}{L_{ref}} - \frac{C_{M_B}}{C_{N_B}} \right) L_{ref}$$

2. Wing (Fixed Surface)

The center of pressure location for the wing must be found before the pitching moment can be specified. The center of pressure of the various lift components are found by the method of Pitts, Nielsen and Kaattari [13]. The lift components are the same as in the lift section. The center of pressure of the lift on the wing in the presence of the body, $(\bar{x})_{W_{(B)}}$, is found from Figure (9-10) if the flow is subsonic and Figure (9-11) if the flow is supersonic.

The center of pressure of the additional lift on the body in the presence of the wing, $(\bar{x})_{B_{(W)}}$, is found using Figure (9-12) if the flow is subsonic. If the flow is supersonic the center of pressure is found from Figure (9-13) or Figure (9-14) depending on the parameters;

$$\beta AR(1 + \lambda)(1 + \frac{1}{m\beta})$$

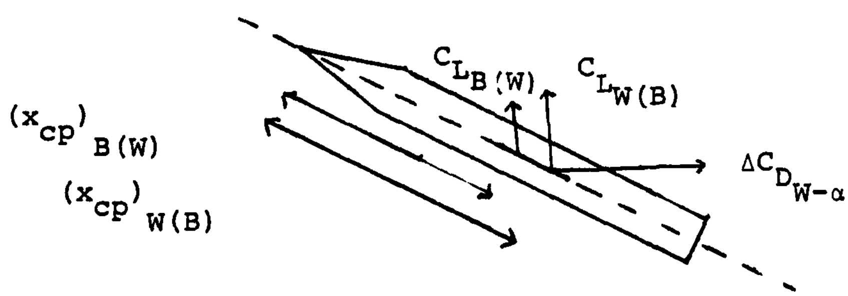
$$\lambda = \text{taper ratio}$$

$$m = \text{co} + \Delta_{LE}$$

If the center of pressure reference is moved to the nose, the following expressions result.

$$(x_{cp})_{W_{(B)}} = (\frac{\bar{x}}{c_r})_{W_{(B)}} (c_r)_W + x_W$$

$$(x_{cp})_{B_{(W)}} = (\frac{\bar{x}}{c_r})_{B_{(W)}} (c_r)_W + x_W$$



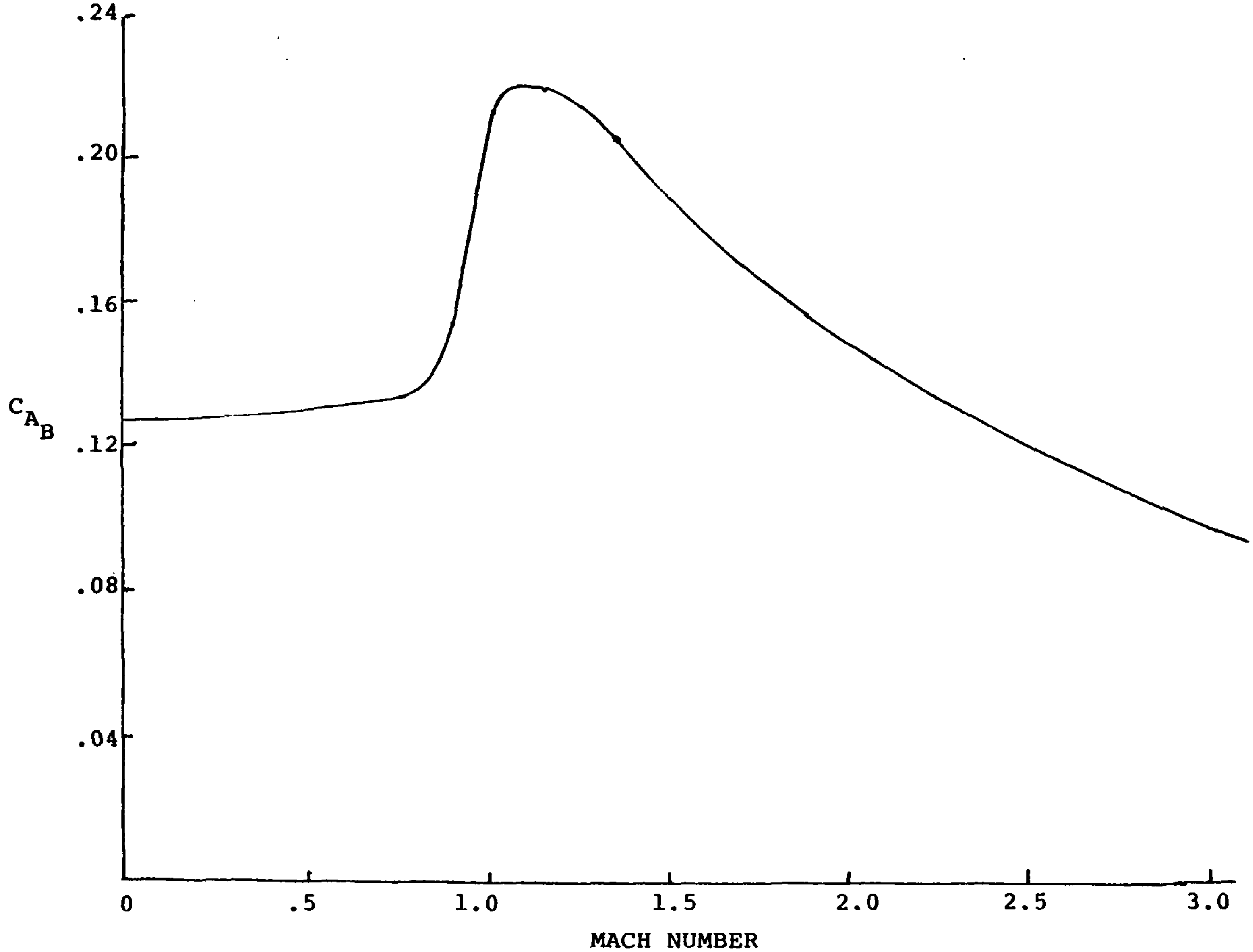


Figure (9-9). Mean base pressure curve.

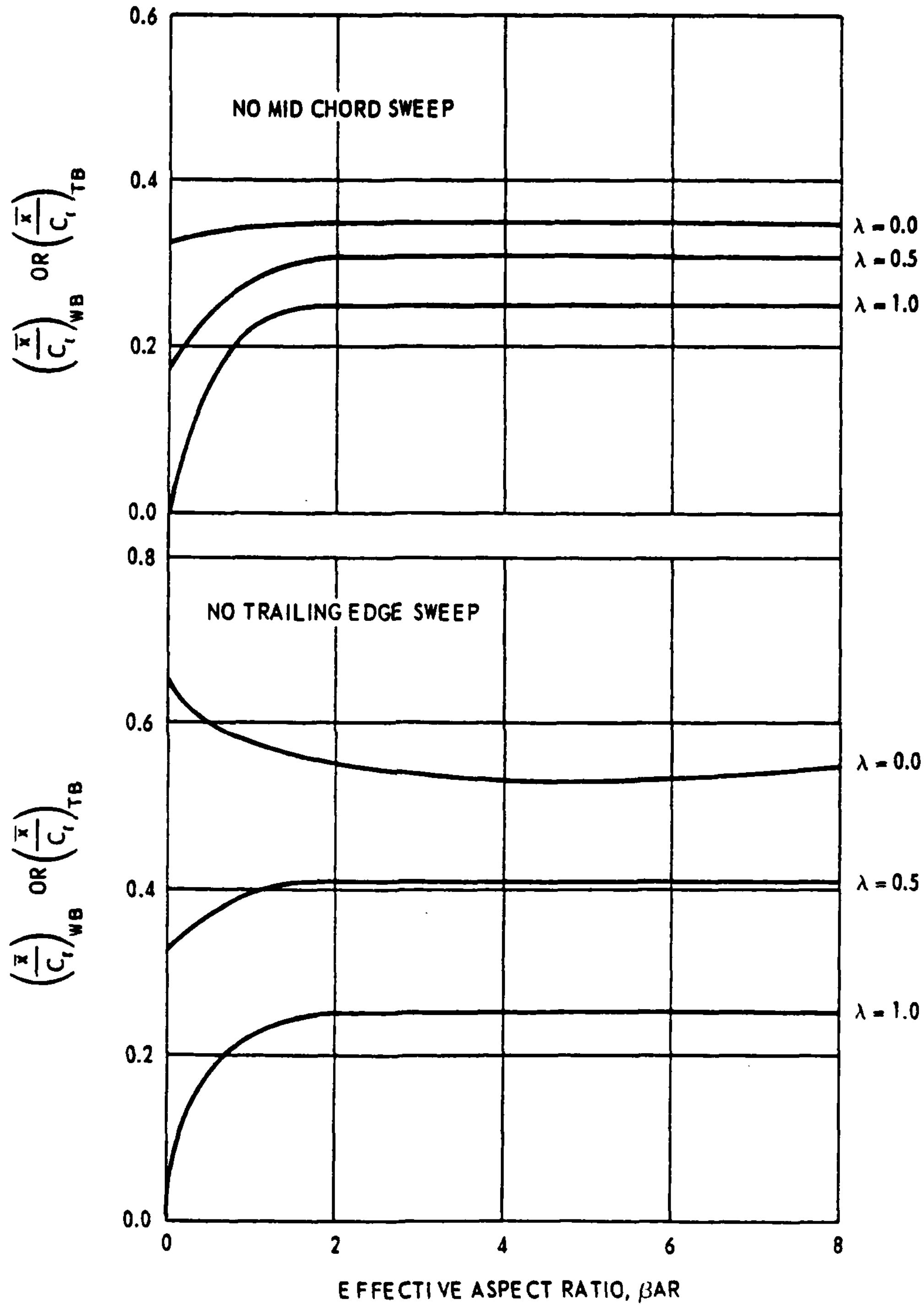


Figure (9-10). Wing center of pressure (subsonic) [18].

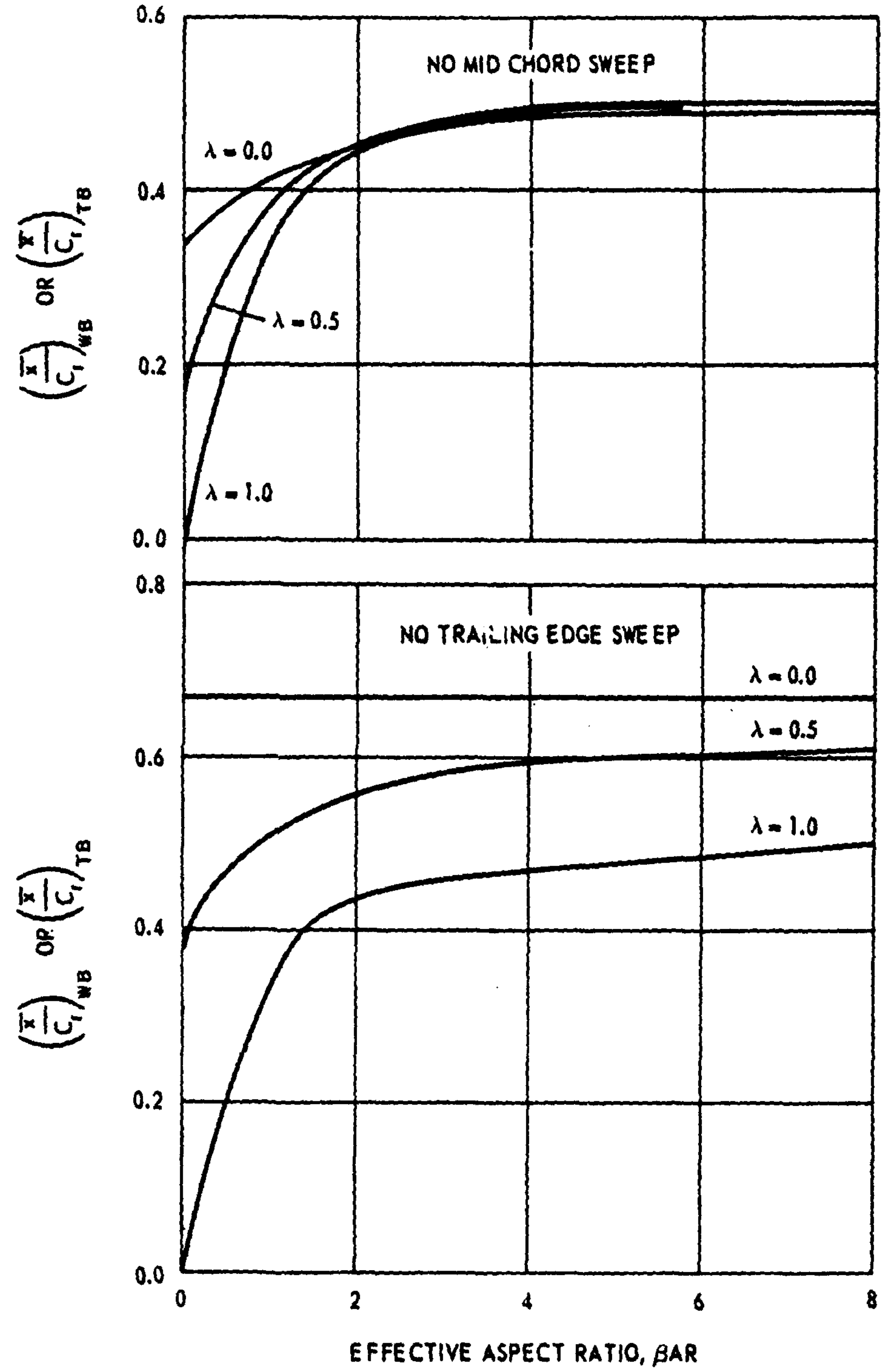


Figure (9-11). Wing center of pressure (supersonic) [18].

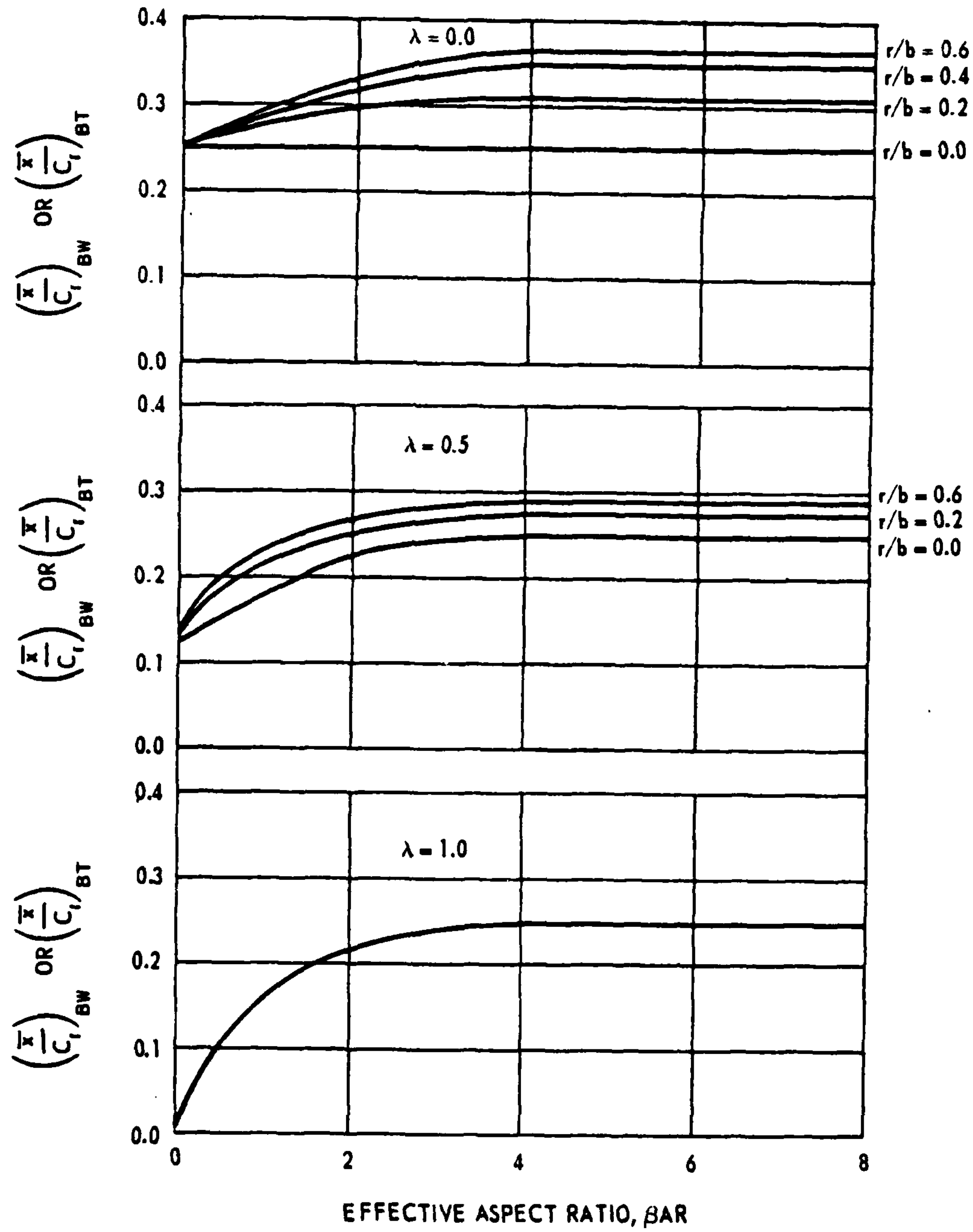


Figure (9-12). Body center of pressure [18].

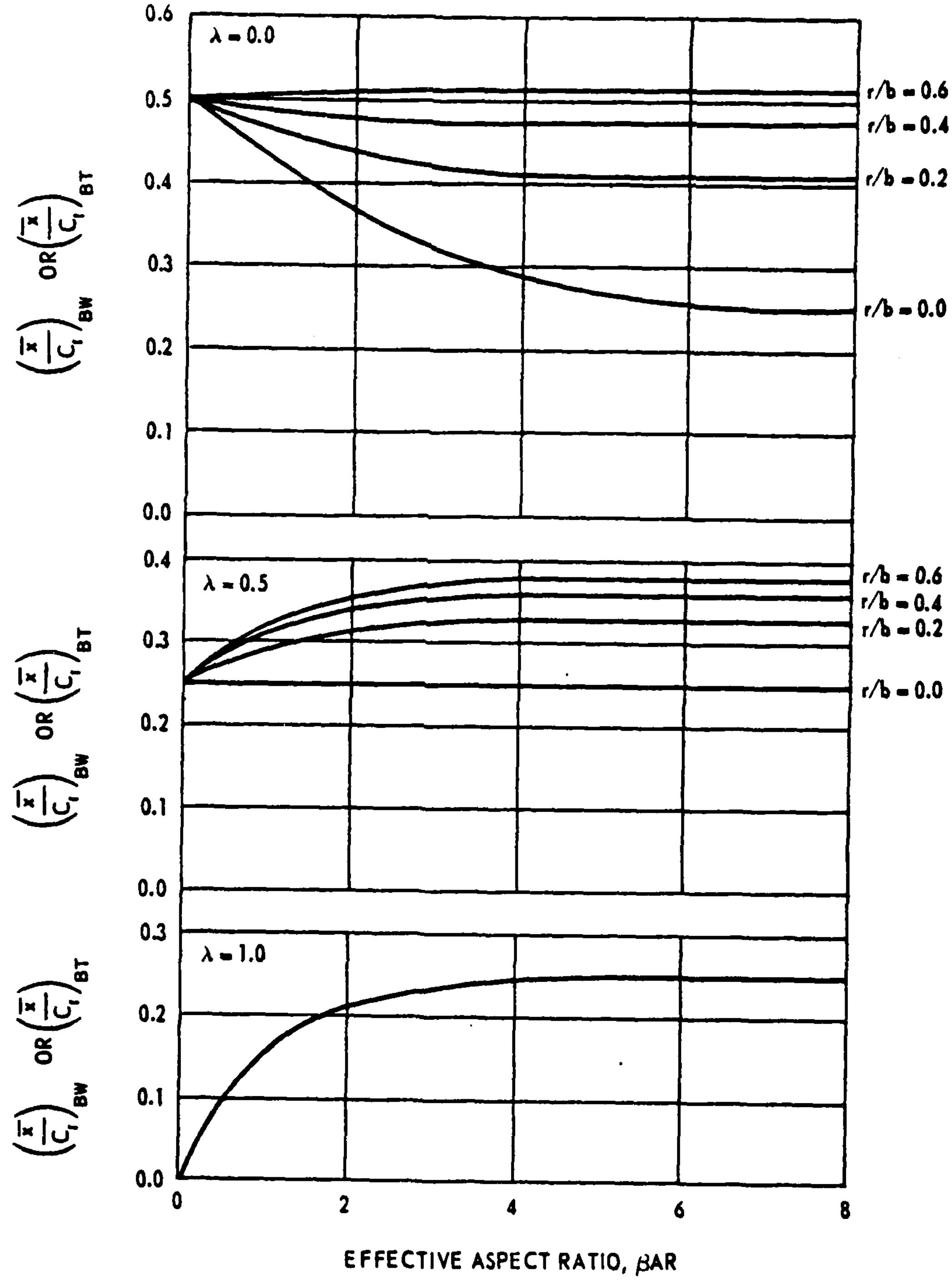


Figure (9-13). Body center of pressure [18].

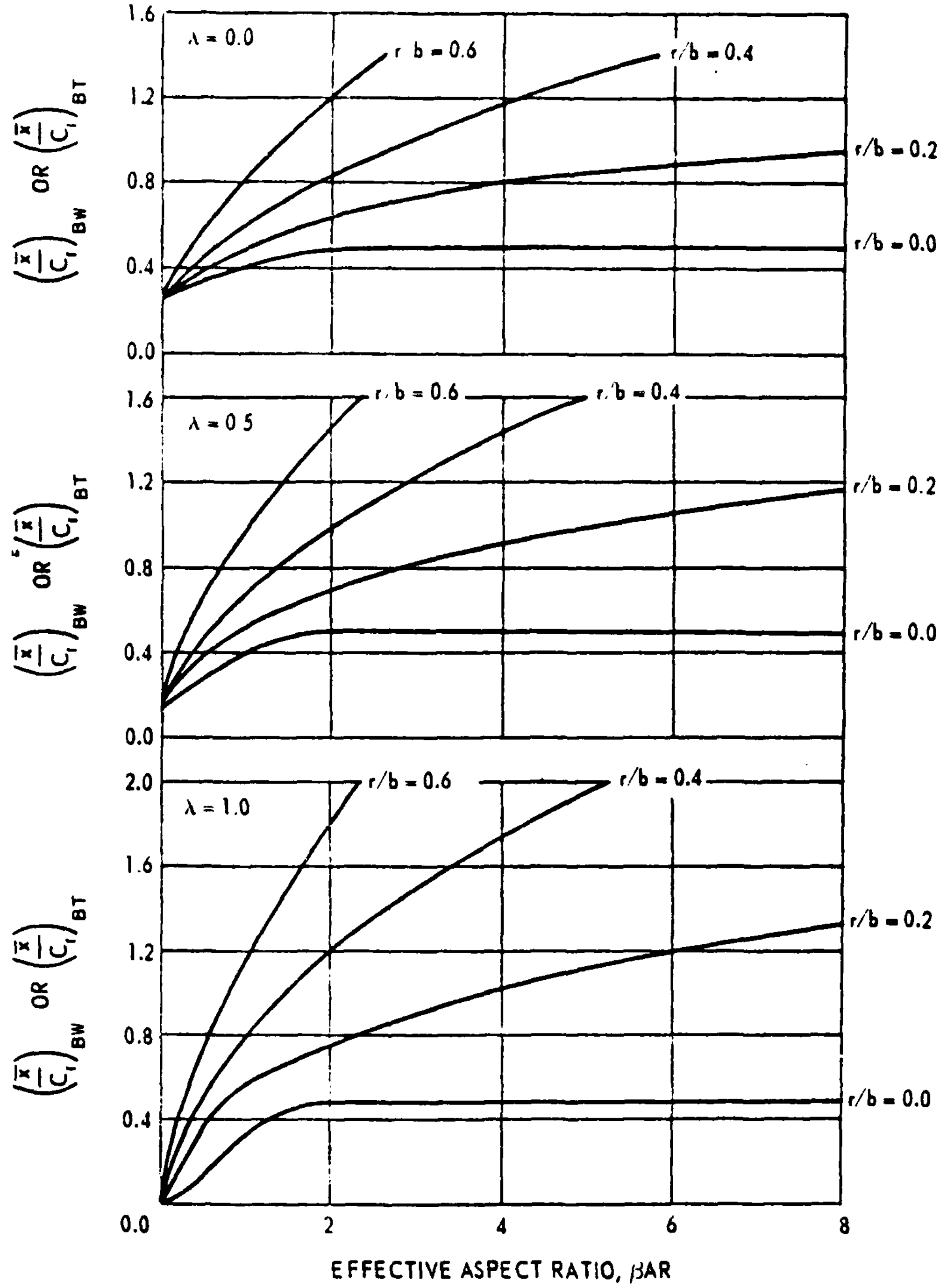


Figure (9-14). Body center of pressure [18].

From the above figure the entire pitching moment about the nose of the missile due to the forces acting on the wing is,

$$C_{M_W} = [(C_{L_{W(B)}} + C_{L_{W(V)}} + C_{L_i})\cos\alpha + \Delta C_{D_{W-\alpha}} \sin\alpha](\frac{(x_{cp})_{W(B)}}{L_{ref}})$$

$$+ [C_{L_{B(W)}} \cos\alpha] (\frac{(x_{cp})_{B(W)}}{L_{ref}})$$

The viscous lift, $C_{L_{W(V)}}$ and lift-loss due to downwash, C_{L_i}, are not shown in the figure but are the same forces as found in the lift section. These forces are assumed to be acting through the center of pressure, $(x_{cp})_{W(B)}$.

An average center of pressure of the wing due to all forces acting on it can now be found as

$$(x_{cp})_W = \frac{C_{M_W} L_{ref}}{(C_{L_W} + C_{L_i}) \cos\alpha + \Delta C_{D_{W-\alpha}} \sin\alpha}$$

where

$$C_{L_W} = C_{L_{W(B)}} + C_{L_{B(W)}} + C_{L_{W(V)}}$$

3. <u>Tail (Control Surface)</u>

The tail pitching moment about the nose of the missile is found in the same way except now a control surface deflection must be included. The equations now become

$$C_{M_T} = [(C_{L_{T(B)}} + C_{L_{T(V)}} + C_{L_i})\cos\alpha + C_{L_{T(B)-\delta}} +$$

$$(\Delta C_{D_{T-\alpha}} + \Delta C_{D_{T-\delta}})\sin\alpha] \left(\frac{(x_{cp})_{T(B)}}{L_{ref}}\right)$$

$$+ [C_{L_{B(T)}} \cos\alpha + C_{L_{B(T)-\delta}}] \left(\frac{(x_{cp})_{B(T)}}{L_{ref}}\right)$$

$$(x_{cp})_T = \frac{C_{M_T} L_{ref}}{(C_{L_{T-\alpha}} + C_{L_i})\cos\alpha + C_{L_{T-\delta}} + (\Delta C_{D_{T-\alpha}} + \Delta C_{D_{T-\delta}})\sin\alpha}$$

where,

$$C_{L_{T-\alpha}} = C_{L_{T(B)}} + C_{L_{B(T)}} + C_{L_{T(V)}}$$

$$C_{L_{T-\delta}} = C_{L_{T(B)-\delta}} + C_{L_{B(T)-\delta}}$$

The wing and tail pitching moments above were found about the nose of the missile. Transferring the pitching moments about the center of gravity the complete missile pitching moment becomes

$$C_M = C_{M_B} + C_{M_W}\left[\frac{x_{cG} - (x_{cp})_W}{(x_{cp})_W}\right] + C_{M_T}\left[\frac{x_{cG} - (x_{cp})_T}{(x_{cp})_T}\right]$$

E. AERO1 DESCRIPTION

It can be seen from the preceding description of the aerodynamics of a missile, that the process of obtaining a complete description of the aerodynamic coefficients becomes an involved task. This was the justification for initially using linear aerodynamics. To complete an analysis a fast method of predicting the static aerodynamic characteristics is needed. The method needs to include both linear and nonlinear contributions as well as interference factors and must be applicable to all speed regimes. This analysis lends itself to programming on a digital computer. AERO1 is a modification of the program AEROCF which was developed at the Naval Air Development Center by Mr. F.A. Kuster, Jr. [17]. The program is essentially as written except for calculation of planform areas and centroids. The program was also modified for use on the Naval Postgraduate School CP/CMS system.

AERO1 consists of a main program and three subroutines. The inputs to the program are the geometric characteristics of the missile, the flight conditions, engine and inlet type and the protuberance drag. The output consists of the aerodynamic coefficients for lift, drag and moment. The component contribution to these coefficients are also given. The component and overall center of pressure are also determined.

Subroutine GEOSUB; This subroutine calculates the missile wetted area and the Reynolds number per foot based on the flight altitude.

Subroutine CLASUB; This subroutine calculates the aerodynamic surface lift-curve slopes.

Subroutine CATSUB; This subroutine calculates center of pressure locations, cross-flow drag coefficients, and interference factors.

Main Program; The main program assumes the control surface is the tail. This is regardless of the method of control (Wing, Tail, Canard). Because of this, care must be taken to input the right data for the tail. For instance, if the missile is a wing control missile, the wing data is input as the tail and the tail data as the wing. Figure (9-15) and Table (9-I) give a complete listing of the input data. Table (9-II) is a list of the output data. Appendix A is a listing of the program as modified for use on the Naval Postgraduate School IBM 360 computer.

1. Verification of AERO1

Before using the program an attempt was made to verify its prediction techniques and find any pitfalls in its use. To accomplish this the program was run for various configurations for which experimental data were available, and the results were compared. The comparisons are shown in Figures (9-16) to (9-25) from references [19] - [22] which are NASA technical notes and memoranda which report results of wind tunnel tests for various body-wing-tail combinations. In Figures (9-16) to (9-25) the solid lines are AERO1 predictions.

a. NASA TN D-6996

This technical note presents a method of predicting aerodynamic characteristics for bodies alone at angles of attack from 0 to 180 degrees. Several nose-body combinations are given.

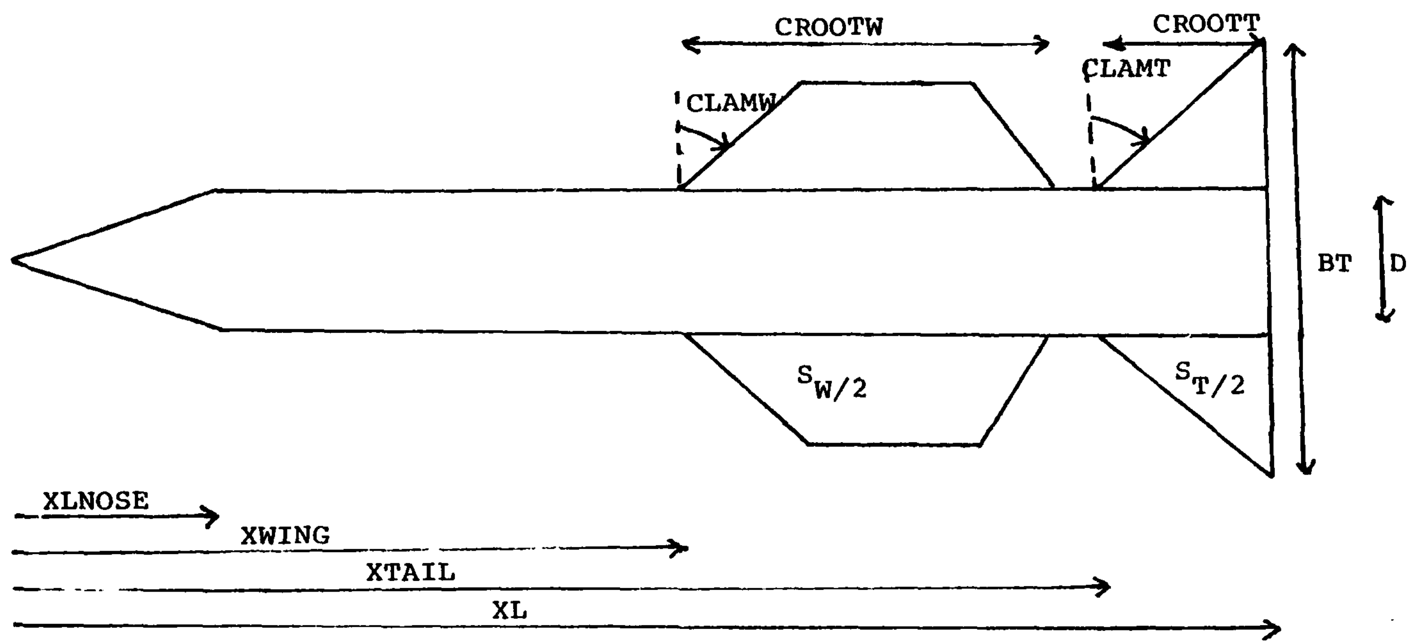


Figure (9-15). AERO1 input data.

TABLE (9-I)

Input Data

Variable	Name	Format	Meaning
1	ICSC	12	Type of control (wing, tail, canard)
2	INOSE	12	Nose shape (ellipsoidal, cone, ogive)
3	IDT	12	Number of control surface deflections
4	IM	12	Numer of Mach numbers
5	IAL	12	Number of angles of attack
6	NBODY	12	Number of configurations
7	ISWPW	12	Wing shape (delta,nondelta)
8	IAFBW	12	Missile body after wing
9	IWEPW	12	Leading edge sweep indicator
10	NWING	12	Number of wings
11	ISWPT	12	Tail shape (delta,nondelta)
12	IAFBT	12	Missile body after tail
13	ISWEPT	12	Leading edge sweep indicator
14	NTAIL	12	Number of tails
15	XLAMW	F10.5	Wing taper ratio
16	CLAMW	F10.5	Wing leading edge sweep
17	BW	F10.5	Wing span
18	CROOTW	F10.5	Wing root chard
19	SW	F10.5	Wing exposed area
20	XMACW	F10.5	Wing mean geometric chord
21	XWING	F10.5	Distance to wing leading edge

Variable	Name	Format	Meaning
22	TOVCW	F10.5	Wing thickness to chord ratio
23	XLAMT	F10.5	Tail taper ratio
24	CLAMT	F10.5	Tail leading edge sweep
25	BT	F10.5	Tail span
26	CROOTT	F10.5	Tail root chord
27	ST	F10.5	Tail exposed area
28	XMACT	F10.5	Tail mean geometric chord
29	XTAIL	F10.5	Distance to tail leading edge
30	TOVCT	F10.5	Tail thickness to chord ratio
31	HT	F10.5	Altitude
32	D	F10.5	body diameter
33	XL	F10.5	Body length
34	XLNOSE	F10.5	Nose length
35	XCG	F10.5	Center of gravity location
36	AREA	F10.5	Reference area
37	XREF	F10.5	Reference length
38	ENGINE	F10.5	Engine code
39	INLET	F10.5	Inlet code
40	BETA	F10.5	Boattail angle
41	DBASE	F10.5	Base diameter
42	DJET	F10.5	Nozzle exit diameter
43	XLABOD	F10.5	Boattail length
44	CDPROT	F10.5	Proturberance drag coefficient

TABLE (9-II)

Output Data

Variable Name	Meaning
AL	Angle of attack
CLTOT	Total coefficient of lift
CDTOT	Total coefficient of drag
CLWP	Wing panel coefficient of lift
CLBW	Additional lift on body due to wing coefficient
CLTP	Tail panel coefficient of lift
CLBT	Additional lift on body due to tail coefficient
CLB	Body alone lift coefficient
CDI	Induced drag coefficient
CNWP	Wing panel normal force coefficient
CNTP	Tail panel normal force coefficient
CLTD	Coefficient of lift due to tail deflection
CDTD	Coefficient of drag due to tail deflection
CN	Total normal force coefficient
CA	Total axial force coefficient
XCPW	Wing center of pressure
XCPT	Tail center of pressure
XCP	Total missile center of pressure
CM	Total pitching moment about center of gravity

Figures (9-16) to (9-18) compare the coefficients predicted by AERO1 with those obtained for body number 9 in the NASA report. The normal force coefficient is predicted well throughout the range. The moment and axial force trends are predicted by the program but large errors exist throughout the range of angles of attack.

b. NASA TM X-2367

This technical memorandum investigates the aerodynamic characteristics of various cruciform body-wing combinations. The coefficients for this configuration agree very well with experimental values up to 10 degrees angle of attack. Beyond this value the lift and moment coefficients predicted by AERO1 exceed the experimental values by as much as 10 percent. Although the exact cause of this error was not investigated, it may be partially explained by the nose shape of the body. The nose is a combination ogive and cone. For purposes of AERO1 it was assumed an ogive. The greater presented area of the ogive would contribute to a higher C_L and C_m through the cross-flow terms in these coefficients. Figures (9-19) through (9-21) compare the predicted with the experimentally determined coefficients for the wing-tail configuration of this reference at M = .9.

c. NASA TM X-2780 and NASA TM X-2289

These technical memoranda investigate the aerodynamics of a delta wing missile using tail control and a tail-less cruciform missile. As shown in Figures (9-22) to (9-25) there is excellent agreement between the experimental values of the aerodynamic coefficients and those predicted by AERO1.

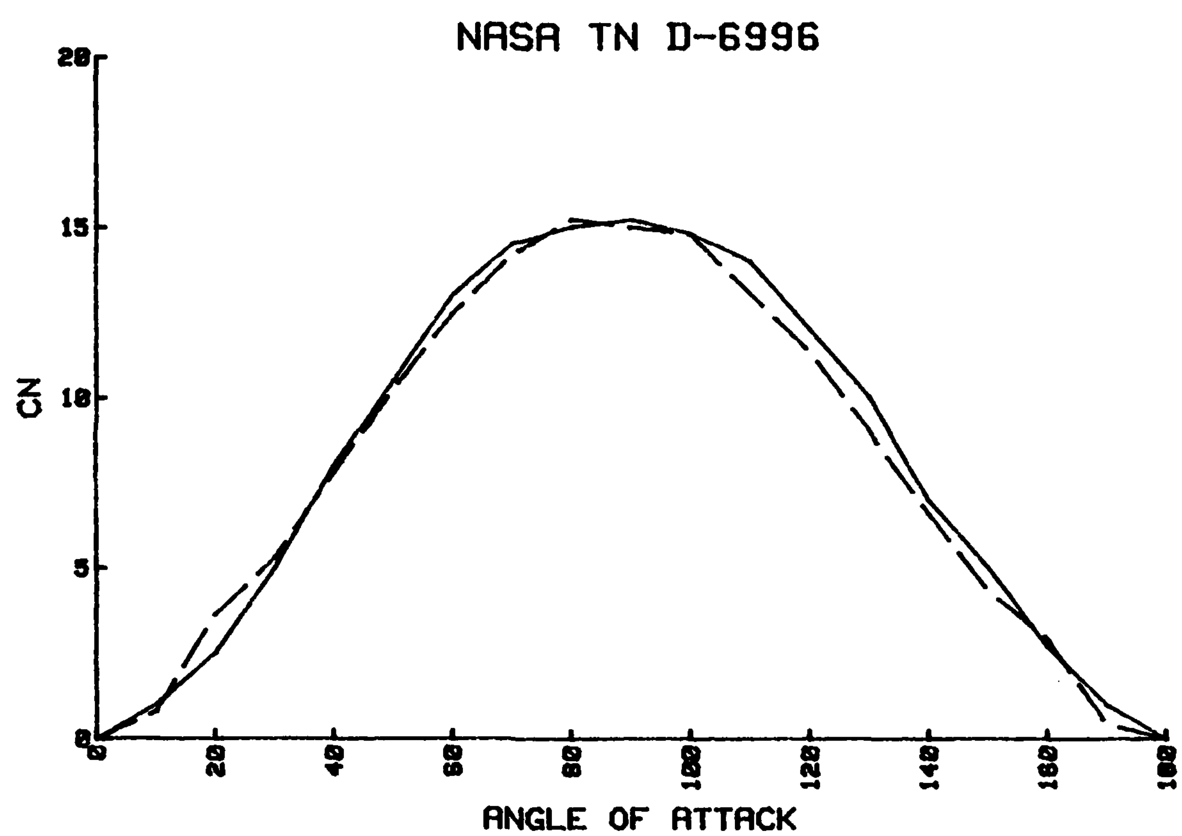


Figure (9-16). Body alone normal force.

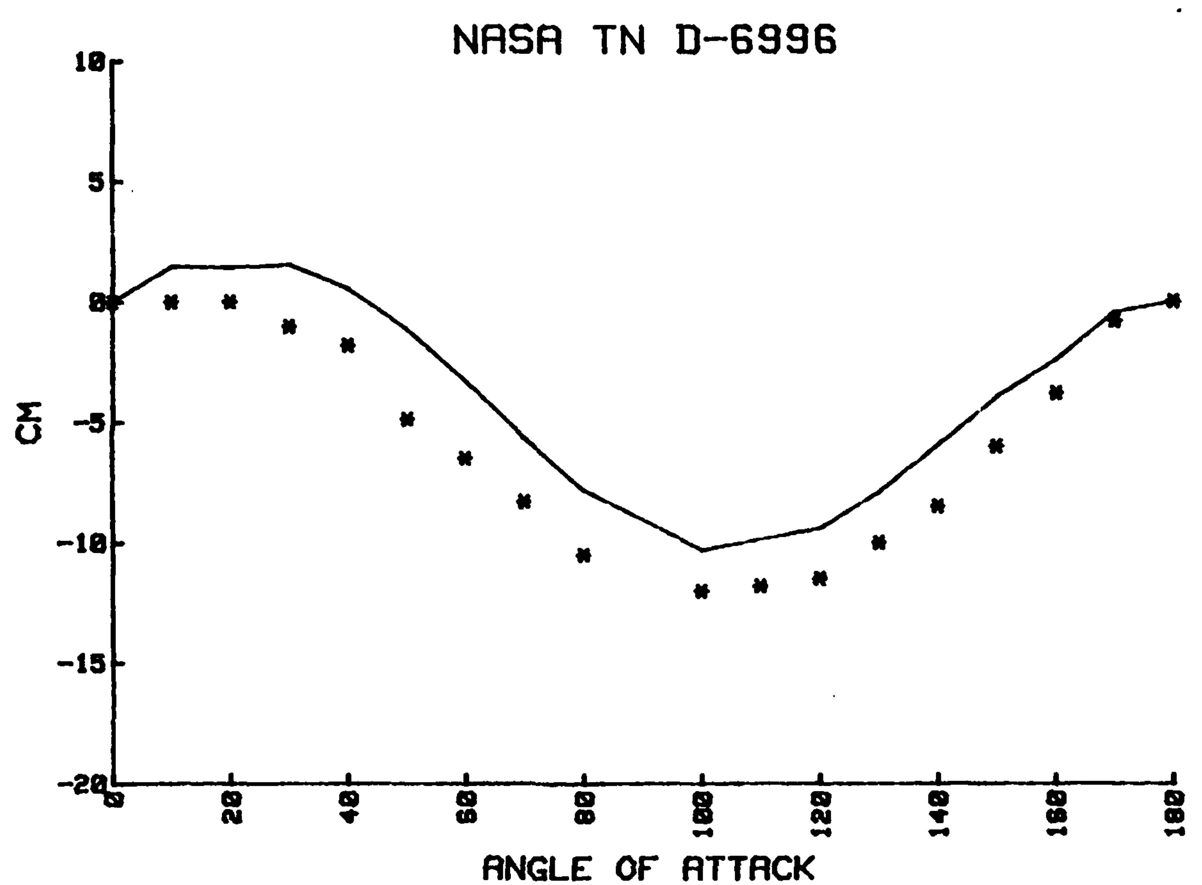


Figure (9-17). Body alone moment.

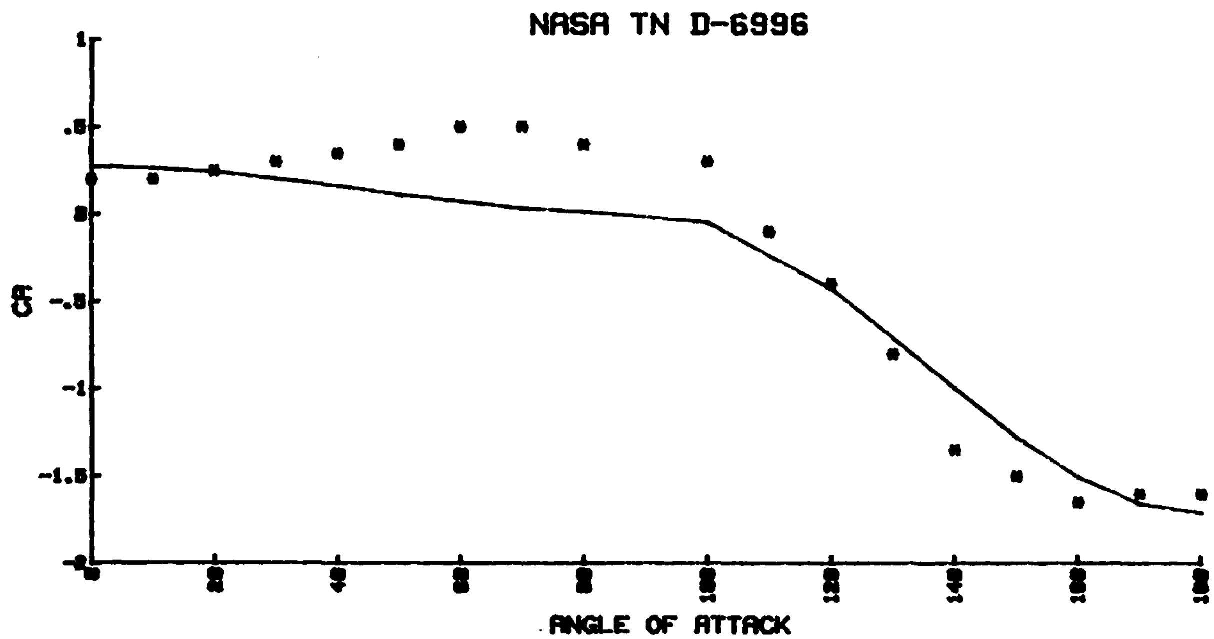


Figure (9-18). Body alone axial force.

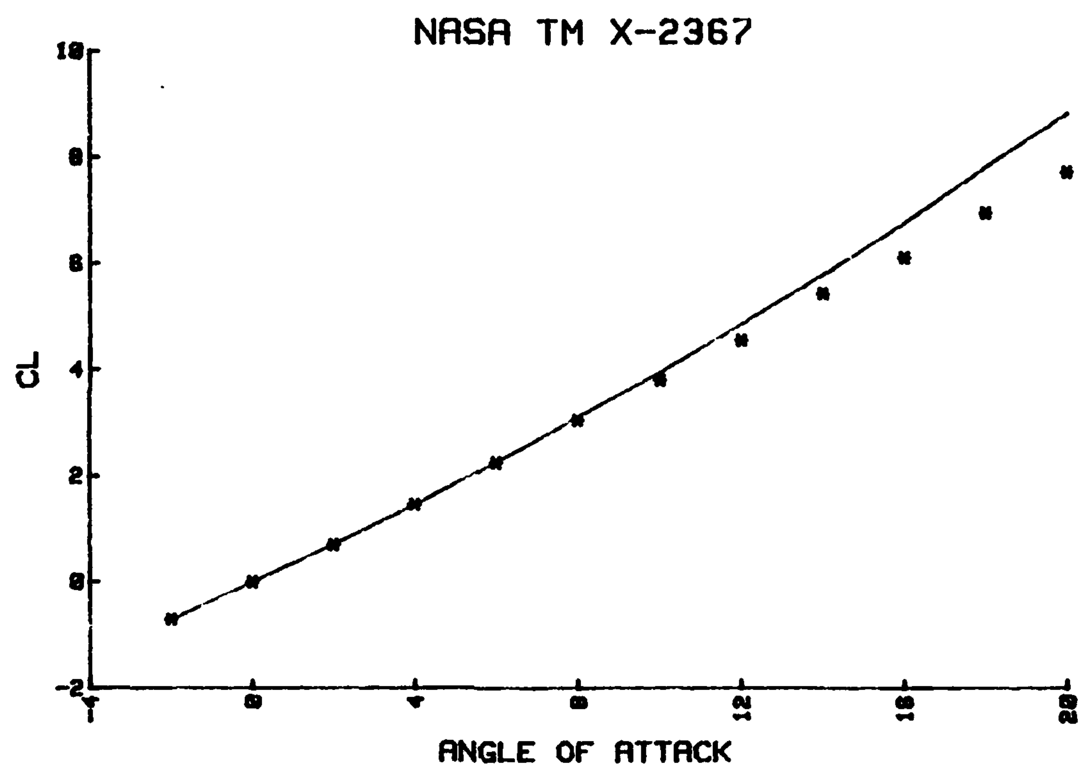


Figure (9-19). Tail-body lift force.

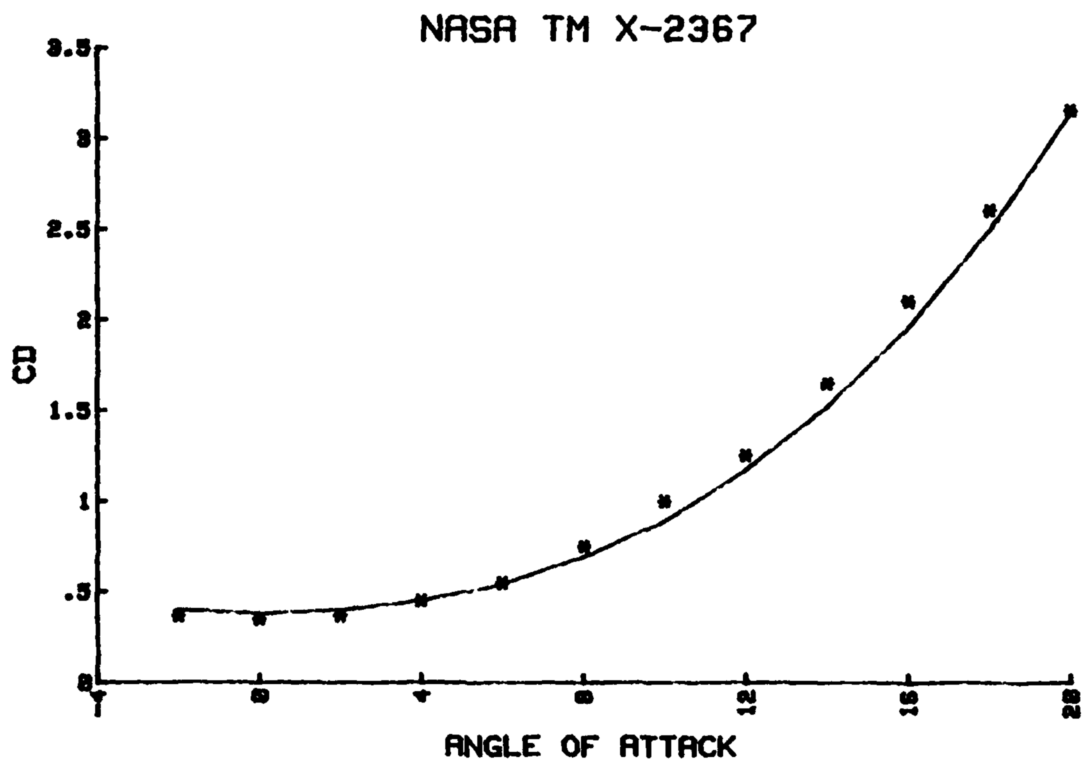


Figure (9-20). Tail-body drag force.

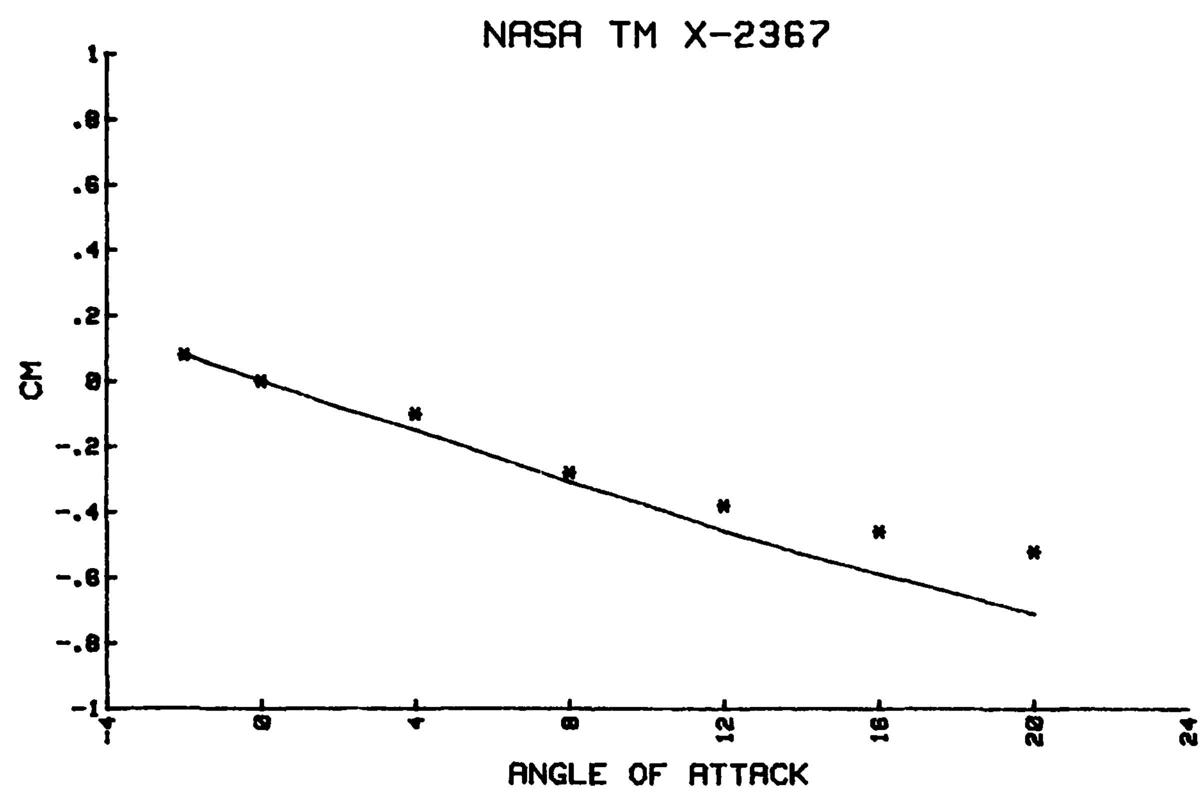


Figure (9-21). Tail-body moment.

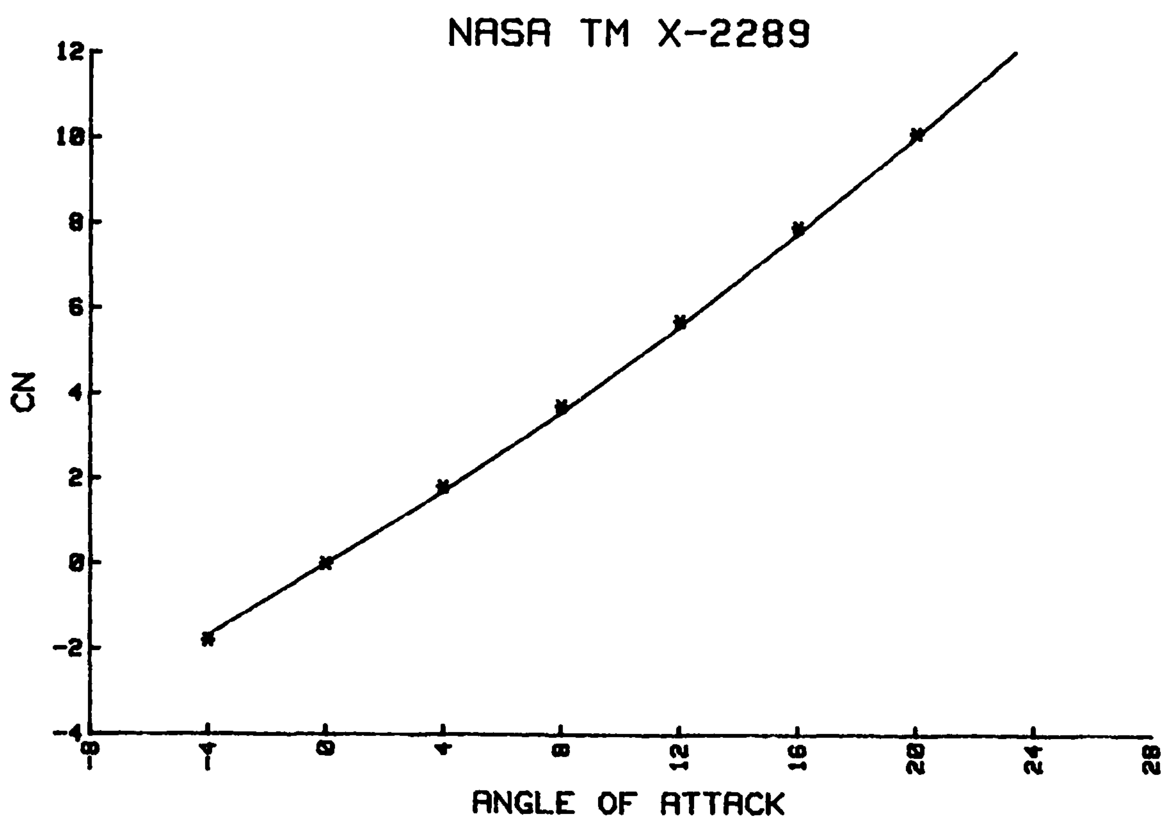


Figure (9-22). Wing-body normal force.

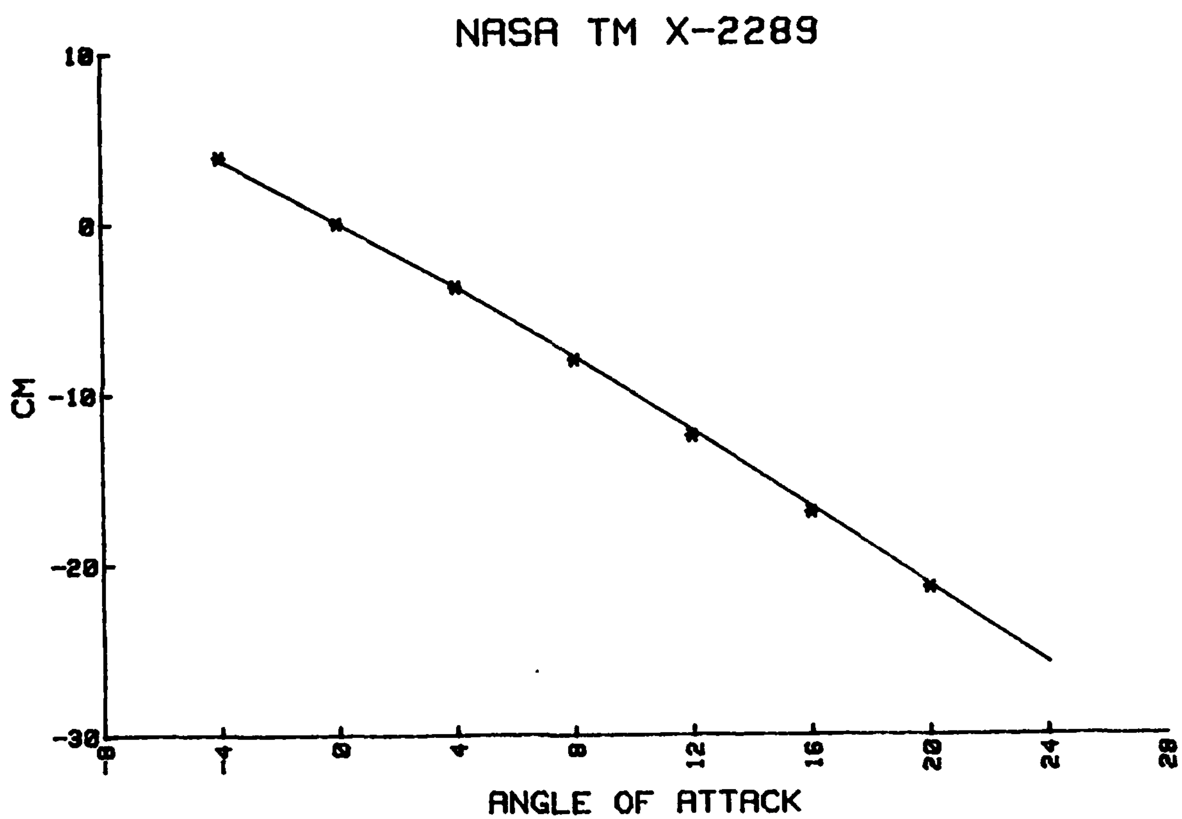


Figure (9-23). Wing-body moment.

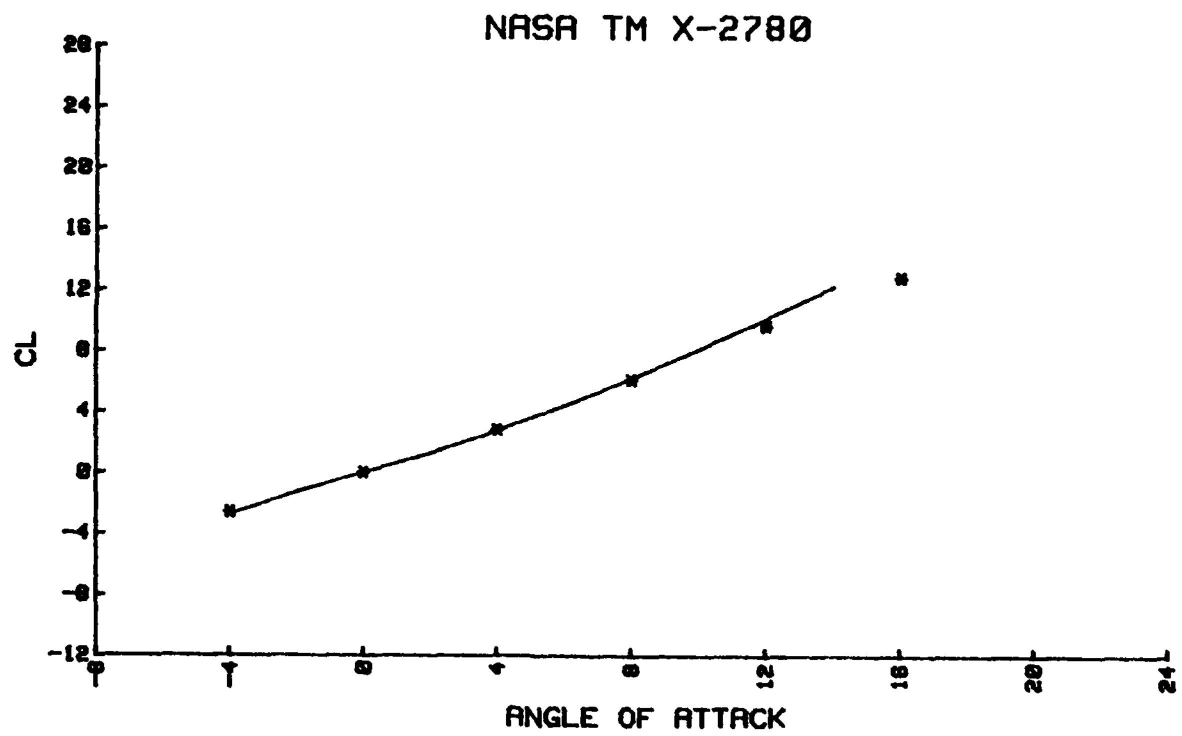


Figure (9-24). Complete missile lift force.

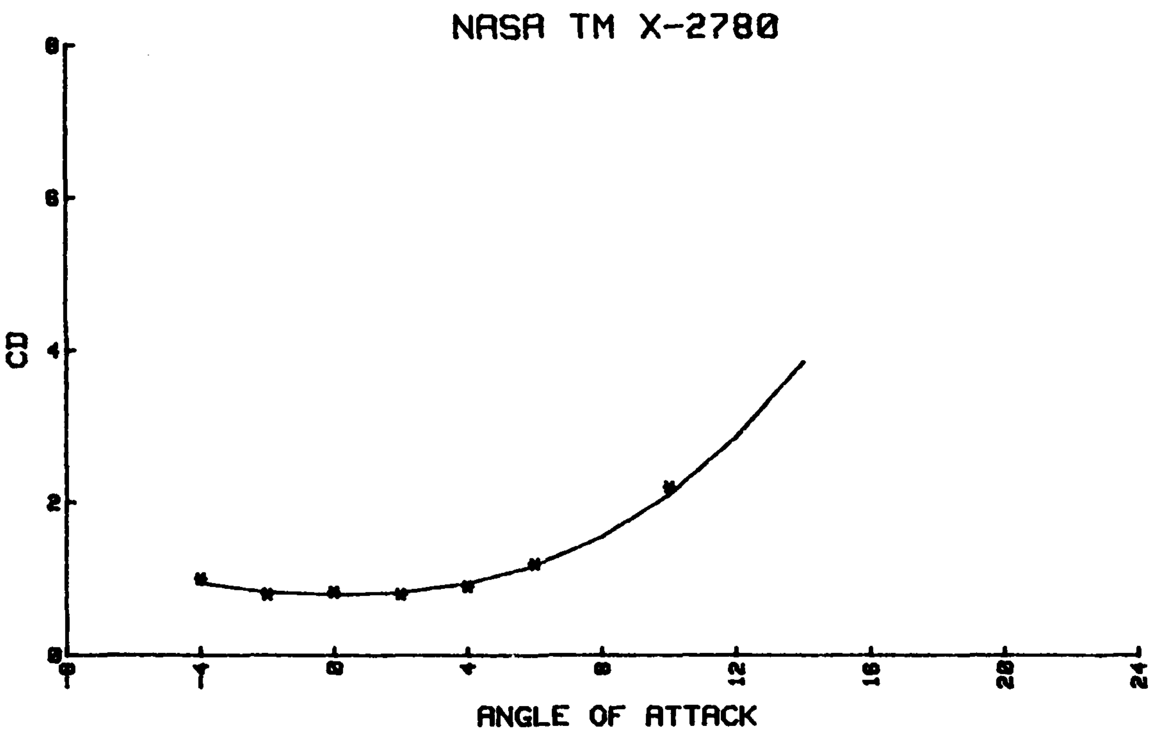


Figure (9-25). Complete missile drag.

F. COMPONENT WEIGHTS

As with the gross weight, the component weights can be determined through the use of parametric regression equations. If the dimensions of the components are known, the following formulas can be used to determine the component weights [7].

Aero Surface Weight

The weight of one wing panel is given by,

$$W_{AS} = 6.77483\ (E_{AS})^{1.02}\ (AR_{AS})^{.56} \tag{1}$$

E_{AS} Exposed are of one panel, ft^2

AR_{AS} Aspect ratio of one panel

Body Structure Weight

$$W_{BS} = .0604\ (L_{BS})^{.64}\ (D_{BS})^{1.77} \tag{2}$$

L_{BS} Length of body to be covered by structure. This does not include the rocket motor unless a separate structure surrounds the motor casing. (inches)

D_{BS} Diameter of body structure (inches)

Internal Systems Weight

$$W_{IS} = .00485\ (W_G)^{.74}\ (L_{IS})^{1.00}\ (D_{IS})^{.42} \tag{3}$$

W_G Gross weight of the missile

L_{IS} Length of subsystem (inches)

D_{IS} Diameter of missile (inches)

In the above equation, the internal system includes guidance, avionics and control.

1. Design Example (Component Sizing)

If the guidance and the control sections are kept at 10 percent of the total length, and the remaining components are as sized previously, the design is as shown in Figure (9-27). Since these components are considered internal systems, their weights can be determined from equation (3).

$$W_{cont} = .00485\ (1809)^{.79}\ (.1L)\ (12.5)^{.42}$$

$$W_{cont} = W_{guid} = 83.64 \text{ lb}$$

The wing and canard weights are found using equation (1) and Figure (9-26).

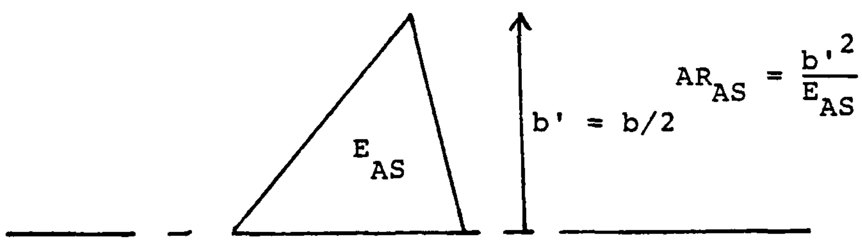


Figure (9-26). Aero surface weight.

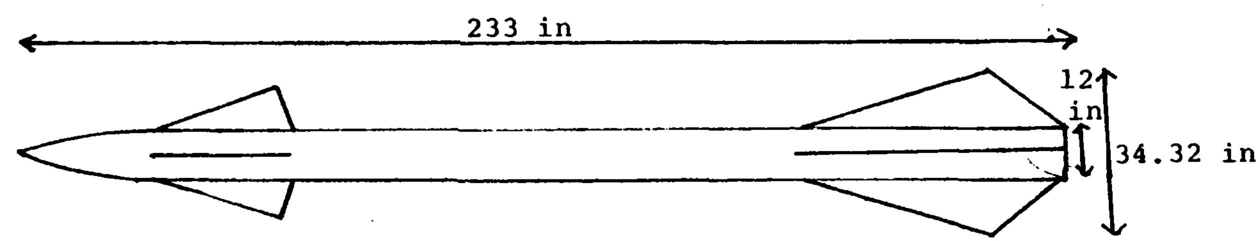


Figure (9-27). Final design.

The wing weight is four times the weight of one panel.

$$W_W = 43.42 \text{ lb}$$

Similarly the canard weight is

$$W_c = 9.88 \text{ lb}$$

If the entire body is covered by structure, the body structure weight becomes

$$W_{st} = .0604\ (232)^{.64}\ (12.5)^{1.77}$$

$$W_{st} = 172.38 \text{ lb}$$

The following component table can now be constructed.

Component	Length (in)	Weight (lbs)	Center of Gravity (in)
Control	23.2	83.64	39.48
Guidance	23.2	83.64	62.68
Warhead	31.25	28.26	89.91
Sustainer	87.51	618.92	149.29
Booster	26.31	159.46	206.20
Motor Casing	113.82	59.50	162.44
Wings		43.42	211.40
Canards		9.88	44.08
Structure	232.00	172.38	116.00

The complete missile weight is then 1264.62 lbs.

The center of gravity from the above table is

$$x_{cG} = 139.44 \text{ in}$$

The center of gravity at the end of boost is

$$(x_{cG}) = 129.85 \text{ in}$$

G. DESIGN EXAMPLE (FINAL ANALYSIS)

From the design parameters so far, a complete description of the missile can be determined. Figure (9-27) is a drawing of the missile. The launch conditions for the missile were specified as,

$$M_M = 1.5$$

$$h = 10{,}000 \text{ ft}$$

$$W_G = 1264.62$$

$$x_{cG} = 139.44 \text{ in}$$

From these conditions the input data for AERO1 is shown in Table (9-III). The format is the same as that of the output of AERO1 and is printed as a check to ensure that the input data was entered properly. The output is shown in Table (9-IV). Figure (9-28) is a plot of the coefficient of moment versus angle of attack for the launch condition and for the beginning of cruise. The center of gravity has moved forward approximately 10 inches for the beginning of cruise so that the stability has

TABLE (9-III). AERO1 Input

AAM LAUNCH CONDITIONS

ICSC	NOSE	NDELT	NMACH	NALPH	NBODY
3	2	1	1	10	1

ISWPW	IAFBW	XLAMW	CLAMW	BW	CROOTW	SW	XMACW	XWING
2	0	0.0	2.860000	2.860000	5.049999	4.700000	3.370000	14.370000

ISWPW2	IAFBW2	XLAMW2	CLAMW2	BW2	CROOW2	SW2	XMACW2	XWING2
0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ISWPT	IAFBT	XLAMT	CLAMT	BT	CROOTT	ST	XMACT	XTAIL
2	1	0.0	75.500000	2.360000	2.750000	1.870000	1.830000	2.559999

HT	D	XL	XLNOSE	XCG	AREA	XREF
10000.000	1.000	19.420	2.320	11.620	0.785	1.000

TOVCW	TOVCW2	TOVCT	ISWEPW	ISWEPT	ISWEP2	NWING	NTAIL	NWING2
0.030	-0.000	0.030	0	0	0	4	4	0

ENGINE	ENLET	BETA	DBASE	DJET	XLOBOD	CDPROT
1.000	0.0	0.0	1.000	0.852	0.0	0.0

TABLE (9-IV). AERO1 Output

VXM= 1.50 DELTA= 0.0

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	-0.64	0.43	-0.13	-0.12	-0.17	-0.07	-0.09	0.02	-0.18	-0.17	0.00	0.00	-0.65	0.41	17.78	4.42	3.38	10.52	-0.71
0.	0.00	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	17.78	4.42	-0.00	8.01	0.00
2.	0.64	0.43	0.13	0.12	0.17	0.07	0.09	0.02	0.18	0.17	0.00	0.00	0.65	0.41	17.78	4.42	3.38	10.52	0.71
4.	1.47	0.52	0.49	0.24	0.35	0.15	0.25	0.11	0.49	0.35	0.00	0.00	1.50	0.41	17.78	4.42	5.06	11.10	0.76
6.	2.43	0.71	0.84	0.37	0.53	0.22	0.47	0.30	0.85	0.54	0.00	0.00	2.47	0.45	17.78	4.42	6.08	11.33	0.72
8.	3.48	1.03	1.22	0.48	0.72	0.29	0.76	0.62	1.23	0.72	0.00	0.00	3.53	0.54	17.78	4.42	6.77	11.43	0.65
10.	4.62	1.52	1.62	0.60	0.91	0.36	1.12	1.11	1.62	0.92	0.00	0.00	4.68	0.69	17.78	4.42	7.27	11.49	0.61
12.	5.83	2.20	2.02	0.71	1.11	0.43	1.55	1.79	2.03	1.11	0.00	0.00	5.91	0.94	17.78	4.42	7.66	11.51	0.63
14.	7.12	3.10	2.44	0.82	1.31	0.49	2.05	2.69	2.45	1.30	0.00	0.00	7.22	1.28	17.78	4.42	7.96	11.52	0.72
16.	8.48	4.25	2.86	0.93	1.50	0.56	2.62	3.85	2.87	1.49	0.00	0.00	8.61	1.75	17.78	4.42	8.22	11.52	0.90

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.3035 CDOW=0.0736 CDOT=0.0320 CDMISC=0.0292 CDOWBT=0.4091

DO YOU WANT ANOTHER RUN, 0=YES, 1=NO
01
P; T=2.14/5.71 15.44.25

VXM= 3.00 DELTA= 0.0

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	-0.53	0.38	-0.18	-0.07	-0.14	-0.05	-0.09	0.01	-0.18	-0.14	0.00	0.00	-0.55	0.36	17.78	4.42	3.38	10.50	-0.17
0.	0.00	0.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.36	17.78	4.42	-0.00	8.42	0.00
2.	0.53	0.38	0.18	0.07	0.14	0.05	0.09	0.01	0.18	0.14	0.00	0.00	0.55	0.36	17.78	4.42	3.38	10.50	0.17
4.	1.24	0.45	0.45	0.15	0.29	0.10	0.25	0.08	0.46	0.29	0.00	0.00	1.27	0.36	17.78	4.42	5.10	11.00	-0.23
6.	2.06	0.59	0.77	0.22	0.44	0.15	0.49	0.23	0.77	0.44	0.00	0.00	2.10	0.37	17.78	4.42	6.17	11.20	-0.79
8.	3.00	0.86	1.10	0.29	0.60	0.20	0.81	0.49	1.11	0.60	0.00	0.00	3.05	0.43	17.78	4.42	6.92	11.28	-1.41
10.	4.05	1.28	1.45	0.37	0.76	0.25	1.23	0.91	1.46	0.76	0.00	0.00	4.12	0.55	17.78	4.42	7.48	11.32	-2.04
12.	5.24	1.91	1.82	0.43	0.93	0.29	1.77	1.55	1.82	0.92	0.00	0.00	5.32	0.78	17.78	4.42	7.93	11.32	-2.64
14.	6.60	2.84	2.20	0.50	1.09	0.34	2.47	2.48	2.20	1.09	0.00	0.00	6.71	1.16	17.78	4.42	8.29	11.29	-3.16
16.	8.96	5.02	2.58	0.57	1.26	0.38	4.18	4.66	2.57	1.25	0.00	0.00	9.15	2.35	17.78	4.42	8.86	11.13	-2.85

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.2688 CDOW=0.0664 CDOT=0.0289 CDMISC=0.0301 CDOWBT=0.3642

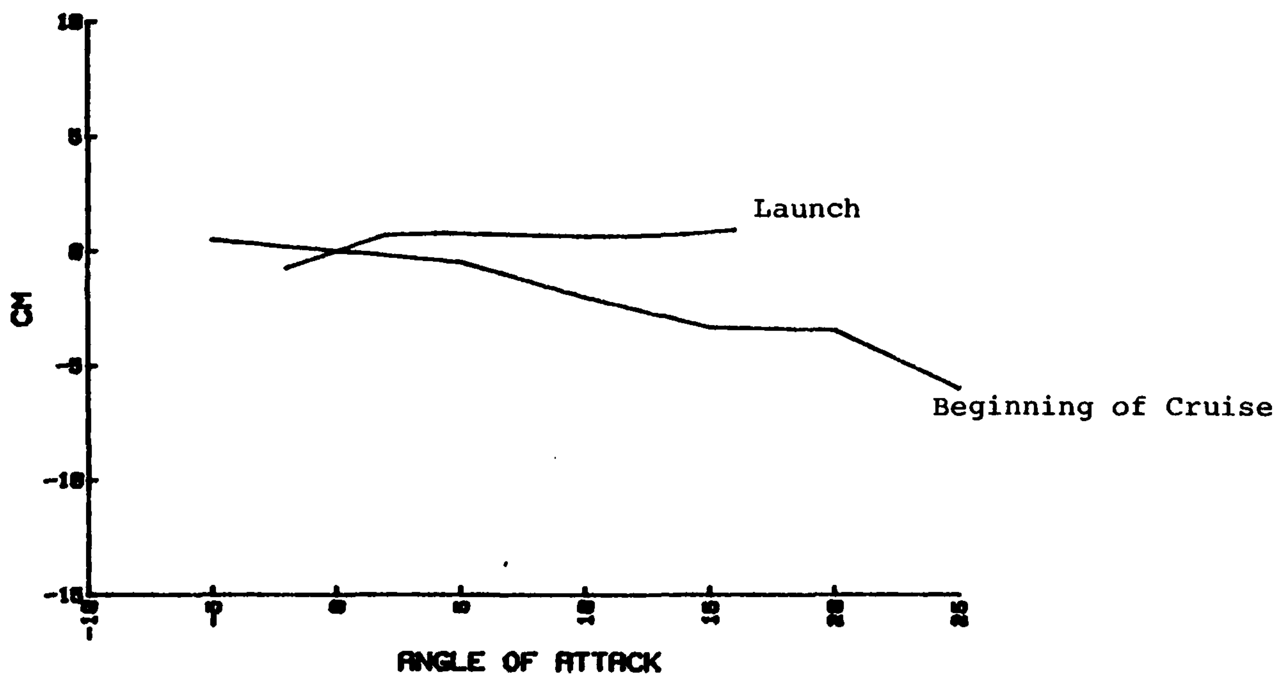


Figure (9-28). Static stability.

increased as indicated in this figure. The performance objective from the beginning of the design was to provide a 31 g maneuver capability. Table (9- V) shows the output of AERO1 for Mach numbers of 1.5 to 3.0 and control deflections of 0.0 to 30 degrees. From this output the trimmed normal force can be found and the corresponding load factor is then,

$$n = \frac{C_{N_{TR}}\ q\ S_{ref}}{W}$$

The following values of maneuver load factor were found using AERO1.

M	$C_{N_{TR}}$	$q(lb/ft^2)$	n(g's)	δ req
2.5	18.80	6369	85.00	10 deg.
2.0	24.50	4076	70.99	10 deg.
1.5	12.00	2293	19.56	10 deg.

As indicated in the above table, the missile meets the maneuvering specifications of the operational requirements.

TABLE (9-V). AERO1 Output

VXM= 1.50 DELTA= 0.0

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	-0.64	0.43	-0.18	-0.12	-0.17	-0.07	-0.09	0.02	-0.18	-0.17	0.00	0.00	-0.65	0.41	17.78	4.42	3.38	10.52	-0.19
0.	0.00	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	17.78	4.42	-0.00	8.01	0.00
2.	0.64	0.43	0.18	0.12	0.17	0.07	0.09	0.02	0.18	0.17	0.00	0.00	0.65	0.41	17.78	4.42	3.38	10.52	0.19
4.	1.48	0.52	0.49	0.24	0.35	0.15	0.25	0.11	0.49	0.35	0.00	0.00	1.50	0.41	17.78	4.42	5.06	11.10	-0.43
6.	2.43	0.71	0.84	0.37	0.53	0.22	0.47	0.30	0.85	0.54	0.00	0.00	2.47	0.45	17.78	4.42	6.08	11.33	-1.25
8.	3.48	1.03	1.22	0.48	0.72	0.29	0.76	0.62	1.23	0.72	0.00	0.00	3.53	0.54	17.78	4.42	6.77	11.43	-2.17
10.	4.62	1.52	1.62	0.60	0.92	0.36	1.12	1.11	1.62	0.92	0.00	0.00	4.68	0.69	17.78	4.42	7.27	11.49	-3.13
12.	5.83	2.20	2.02	0.71	1.11	0.43	1.55	1.79	2.03	1.11	0.00	0.00	5.91	0.94	17.78	4.42	7.66	11.51	-4.10
14.	7.12	3.10	2.44	0.83	1.31	0.49	2.05	2.69	2.45	1.30	0.00	0.00	7.22	1.28	17.78	4.42	7.96	11.52	-5.06
16.	8.48	4.26	2.86	0.93	1.50	0.56	2.63	3.85	2.87	1.50	0.00	0.00	8.61	1.75	17.78	4.42	8.22	11.52	-5.99

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.3036 CDOW=0.0736 CDOT=0.0321 CDMISC=0.0292 CDOWBT=0.4092

VXM= 1.50 DELTA= 10.00

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	0.19	0.43	-0.12	-0.12	0.28	0.24	-0.09	0.00	-0.12	0.28	0.51	0.02	0.18	0.44	17.78	4.42	3.38	*****	4.29
0.	0.92	0.46	0.00	0.00	0.61	0.31	0.00	0.04	0.00	0.61	0.51	0.02	0.92	0.46	17.78	4.42	-0.00	4.42	5.86
2.	1.52	0.53	0.12	0.12	0.81	0.38	0.09	0.10	0.12	0.81	0.51	0.02	1.53	0.48	17.78	4.42	3.38	6.46	6.69
4.	2.40	0.69	0.44	0.24	1.02	0.45	0.25	0.27	0.44	1.02	0.50	0.02	2.43	0.52	17.78	4.42	5.06	8.28	6.17
6.	3.39	0.97	0.80	0.37	1.23	0.52	0.47	0.54	0.81	1.24	0.50	0.02	3.43	0.61	17.78	4.42	6.08	9.24	5.44
8.	4.47	1.39	1.19	0.48	1.44	0.59	0.76	0.97	1.20	1.45	0.49	0.02	4.53	0.76	17.78	4.42	6.77	9.80	4.61
10.	5.63	1.99	1.59	0.60	1.66	0.66	1.12	1.56	1.60	1.67	0.49	0.02	5.70	0.98	17.78	4.42	7.27	10.16	3.74
12.	6.87	2.79	2.00	0.71	1.87	0.72	1.55	2.36	2.01	1.89	0.48	0.01	6.95	1.30	17.78	4.42	7.66	10.41	2.84
14.	8.17	3.81	2.42	0.83	2.08	0.78	2.05	3.39	2.43	2.10	0.47	0.01	8.28	1.72	17.78	4.42	7.96	10.59	1.93
16.	9.54	5.10	2.85	0.93	2.29	0.84	2.63	4.68	2.85	2.30	0.47	0.01	9.67	2.27	17.78	4.42	8.22	10.71	1.03

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.3036 CDOW=0.0736 CDOT=0.0321 CDMISC=0.0292 CDOWBT=0.4092

VXM= 1.50 DELTA= 20.00

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	0.76	0.50	-0.05	-0.12	0.51	0.52	-0.09	0.03	-0.05	0.51	0.97	0.06	0.75	0.52	17.78	4.42	3.38	1.39	7.06
0.	1.89	0.62	0.00	0.00	1.31	0.58	0.00	0.16	0.00	1.31	0.96	0.06	1.89	0.62	17.78	4.42	-0.00	4.42	12.13
2.	2.44	0.73	0.05	0.12	1.53	0.65	0.09	0.26	0.05	1.54	0.95	0.06	2.46	0.64	17.78	4.42	3.38	5.34	13.49
4.	3.32	0.96	0.36	0.24	1.75	0.71	0.25	0.49	0.37	1.76	0.93	0.06	3.35	0.73	17.78	4.42	5.06	6.92	13.10
6.	4.33	1.33	0.75	0.37	1.97	0.78	0.47	0.86	0.76	1.99	0.92	0.05	4.39	0.87	17.78	4.42	6.08	8.03	12.22
8.	5.42	1.84	1.15	0.48	2.19	0.84	0.76	1.38	1.16	2.21	0.90	0.05	5.49	1.07	17.78	4.42	6.77	8.76	11.31
10.	6.58	2.53	1.56	0.60	2.40	0.90	1.12	2.07	1.57	2.43	0.88	0.05	6.67	1.35	17.78	4.42	7.27	9.27	10.35
12.	7.81	3.42	1.98	0.71	2.60	0.95	1.55	2.96	1.99	2.64	0.87	0.05	7.92	1.72	17.78	4.42	7.66	9.64	9.34
14.	9.10	4.54	2.40	0.83	2.80	1.01	2.05	4.09	2.41	2.85	0.85	0.05	9.23	2.21	17.78	4.42	7.96	9.92	8.30
16.	10.44	5.92	2.83	0.93	2.99	1.06	2.63	5.47	2.84	3.04	0.83	0.04	10.61	2.81	17.78	4.42	8.22	10.14	7.23

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.3036 CDOW=0.0736 CDOT=0.0321 CDMISC=0.0292 CDOWBT=0.4092

VXM= 1.50 DELTA= 30.00

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	0.91	0.56	-0.13	-0.12	0.53	0.73	-0.09	0.04	-0.14	0.52	1.32	0.11	0.89	0.59	17.78	4.42	3.38	0.62	9.08
0.	2.77	0.85	0.00	0.00	1.99	0.79	0.00	0.34	0.00	1.99	1.29	0.11	2.77	0.85	17.78	4.42	-0.00	4.42	17.75
2.	3.38	1.01	0.13	0.12	2.20	0.84	0.09	0.50	0.14	2.21	1.26	0.10	3.41	0.90	17.78	4.42	3.38	5.41	18.45
4.	4.04	1.23	0.24	0.24	2.40	0.90	0.25	0.73	0.25	2.42	1.24	0.10	4.08	0.95	17.78	4.42	5.06	6.08	19.34
6.	5.07	1.67	0.68	0.37	2.60	0.95	0.47	1.17	0.69	2.64	1.21	0.09	5.14	1.13	17.78	4.42	6.08	7.32	17.98
8.	6.15	2.24	1.10	0.48	2.79	1.00	0.76	1.75	1.11	2.84	1.18	0.09	6.24	1.37	17.78	4.42	6.77	8.14	16.73
10.	7.28	2.99	1.52	0.60	2.98	1.06	1.12	2.49	1.53	3.04	1.14	0.08	7.39	1.68	17.78	4.42	7.27	8.73	15.47
12.	8.47	3.93	1.95	0.71	3.15	1.10	1.55	3.44	1.96	3.22	1.11	0.08	8.61	2.08	17.78	4.42	7.66	9.18	14.16
14.	9.72	5.08	2.38	0.83	3.31	1.15	2.05	4.60	2.39	3.39	1.07	0.07	9.88	2.58	17.78	4.42	7.96	9.53	12.79
16.	11.02	6.48	2.81	0.93	3.46	1.19	2.63	6.01	2.82	3.55	1.04	0.07	11.22	3.20	17.78	4.42	8.22	9.81	11.37

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.3036 CDOW=0.0736 CDOT=0.0321 CDMISC=0.0292 CDOWBT=0.4092

VXM= 2.00 DELTA= 0.0

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	-0.60	0.41	-0.18	-0.11	-0.16	-0.06	-0.09	0.02	-0.18	-0.16	0.00	0.00	-0.61	0.39	17.78	4.42	3.38	10.50	-0.20
0.	0.00	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	17.78	4.42	-0.00	8.15	0.00
2.	0.60	0.41	0.18	0.11	0.16	0.06	0.09	0.02	0.18	0.16	0.00	0.00	0.61	0.39	17.78	4.42	3.38	10.50	0.20
4.	1.39	0.49	0.48	0.22	0.33	0.13	0.25	0.10	0.48	0.33	0.00	0.00	1.42	0.39	17.78	4.42	5.07	11.05	-0.33
6.	2.30	0.67	0.81	0.32	0.50	0.19	0.48	0.27	0.82	0.50	0.00	0.00	2.34	0.42	17.78	4.42	6.11	11.27	-1.04
8.	3.31	0.97	1.18	0.43	0.68	0.25	0.78	0.57	1.19	0.68	0.00	0.00	3.36	0.50	17.78	4.42	6.81	11.37	-1.84
10.	4.41	1.42	1.56	0.53	0.86	0.31	1.15	1.03	1.57	0.86	0.00	0.00	4.47	0.64	17.78	4.42	7.33	11.42	-2.68
12.	5.60	2.08	1.95	0.63	1.04	0.37	1.61	1.68	1.96	1.04	0.00	0.00	5.68	0.87	17.78	4.42	7.73	11.44	-3.51
14.	6.89	2.96	2.35	0.73	1.23	0.43	2.15	2.57	2.36	1.23	0.00	0.00	6.99	1.21	17.78	4.42	8.05	11.44	-4.32
16.	8.27	4.13	2.76	0.82	1.42	0.48	2.79	3.74	2.76	1.41	0.00	0.00	8.40	1.69	17.78	4.42	8.32	11.42	-5.08

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.2912 CDOW=0.0705 CDOT=0.0307 CDMISC=0.0292 CDOWBT=0.3924

VXM= 2.00 DELTA= 10.00

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	0.16	0.41	-0.12	-0.11	0.26	0.23	-0.09	0.00	-0.13	0.26	0.48	0.01	0.15	0.42	17.78	4.42	3.38	*****	3.90
0.	0.86	0.44	0.00	0.00	0.57	0.29	0.00	0.03	0.00	0.57	0.48	0.01	0.86	0.44	17.78	4.42	-0.00	4.50	5.43
2.	1.44	0.50	0.12	0.11	0.76	0.35	0.09	0.09	0.13	0.77	0.47	0.01	1.45	0.45	17.78	4.42	3.38	6.54	6.21
4.	2.27	0.65	0.43	0.22	0.96	0.41	0.25	0.24	0.44	0.97	0.47	0.01	2.30	0.49	17.78	4.42	5.07	8.30	5.79
6.	3.21	0.90	0.78	0.32	1.16	0.47	0.48	0.49	0.79	1.17	0.46	0.01	3.25	0.56	17.78	4.42	6.11	9.23	5.18
8.	4.25	1.29	1.15	0.43	1.37	0.53	0.78	0.88	1.16	1.37	0.46	0.01	4.30	0.69	17.78	4.42	6.81	9.78	4.49
10.	5.37	1.85	1.54	0.53	1.57	0.59	1.15	1.44	1.54	1.58	0.45	0.01	5.44	0.89	17.78	4.42	7.33	10.13	3.75
12.	6.59	2.61	1.93	0.63	1.77	0.64	1.61	2.21	1.94	1.78	0.45	0.01	6.67	1.19	17.78	4.42	7.73	10.37	3.00
14.	7.89	3.62	2.34	0.73	1.97	0.69	2.15	3.21	2.34	1.98	0.44	0.01	7.99	1.60	17.78	4.42	8.05	10.54	2.24
16.	9.28	4.91	2.75	0.82	2.17	0.75	2.79	4.51	2.75	2.18	0.43	0.01	9.42	2.17	17.78	4.42	8.32	10.66	1.51

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.2912 CDOW=0.0705 CDOT=0.0307 CDMISC=0.0292 CDOWBT=0.3924

VXM= 2.00 DELTA= 20.00

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	0.68	0.47	-0.07	-0.11	0.46	0.49	-0.09	0.02	-0.07	0.45	0.90	0.05	0.66	0.49	17.78	4.42	3.38	1.28	6.33
0.	1.79	0.58	0.00	0.00	1.25	0.54	0.00	0.14	0.00	1.25	0.89	0.05	1.79	0.58	17.78	4.42	-0.00	4.50	11.31
2.	2.32	0.68	0.07	0.11	1.45	0.60	0.09	0.24	0.07	1.46	0.88	0.05	2.33	0.60	17.78	4.42	3.38	5.43	12.58
4.	3.15	0.89	0.37	0.22	1.66	0.65	0.25	0.45	0.37	1.67	0.87	0.05	3.18	0.67	17.78	4.42	5.07	6.96	12.29
6.	4.11	1.22	0.74	0.32	1.87	0.71	0.48	0.78	0.74	1.89	0.85	0.05	4.16	0.78	17.78	4.42	6.11	8.04	11.56
8.	5.16	1.70	1.12	0.43	2.08	0.76	0.78	1.26	1.12	2.10	0.84	0.05	5.22	0.96	17.78	4.42	6.81	8.75	10.80
10.	6.28	2.34	1.51	0.53	2.28	0.81	1.15	1.91	1.52	2.31	0.82	0.04	6.36	1.22	17.78	4.42	7.33	9.25	9.99
12.	7.49	3.19	1.91	0.63	2.48	0.86	1.61	2.76	1.92	2.51	0.81	0.04	7.59	1.57	17.78	4.42	7.73	9.62	9.13
14.	8.77	4.29	2.32	0.73	2.67	0.91	2.15	3.86	2.33	2.71	0.79	0.04	8.90	2.04	17.78	4.42	8.05	9.89	8.26
16.	10.14	5.67	2.73	0.82	2.85	0.95	2.79	5.24	2.74	2.89	0.77	0.04	10.31	2.66	17.78	4.42	8.32	10.11	7.37

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.2912 CDOW=0.0705 CDOT=0.0307 CDMISC=0.0292 CDOWBT=0.3924

VXM= 2.00 DELTA= 30.00

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	0.79	0.52	-0.14	-0.11	0.45	0.68	-0.09	0.03	-0.14	0.44	1.23	0.10	0.78	0.55	17.78	4.42	3.38	0.52	7.99
0.	2.63	0.73	0.00	0.00	1.90	0.73	0.00	0.30	0.00	1.90	1.20	0.09	2.63	0.79	17.78	4.42	-0.00	4.49	16.64
2.	3.22	0.94	0.14	0.11	2.10	0.78	0.09	0.45	0.14	2.11	1.18	0.09	3.24	0.82	17.78	4.42	3.38	5.47	17.33
4.	3.85	1.14	0.26	0.22	2.29	0.83	0.25	0.66	0.27	2.31	1.15	0.09	3.89	0.87	17.78	4.42	5.07	6.15	18.18
6.	4.83	1.53	0.67	0.32	2.49	0.87	0.48	1.06	0.68	2.52	1.12	0.08	4.89	1.02	17.78	4.42	6.11	7.34	17.01
8.	5.86	2.06	1.07	0.43	2.67	0.92	0.78	1.60	1.08	2.71	1.09	0.08	5.94	1.23	17.78	4.42	6.81	8.14	15.94
10.	6.96	2.76	1.48	0.53	2.84	0.96	1.15	2.30	1.48	2.90	1.06	0.07	7.06	1.51	17.78	4.42	7.33	8.72	14.85
12.	8.13	3.66	1.89	0.63	3.01	1.00	1.61	3.20	1.89	3.07	1.03	0.07	8.26	1.89	17.78	4.42	7.73	9.16	13.70
14.	9.37	4.79	2.30	0.73	3.16	1.03	2.15	4.34	2.31	3.23	1.00	0.06	9.53	2.38	17.78	4.42	8.05	9.51	12.51
16.	10.70	6.20	2.72	0.82	3.30	1.07	2.79	5.75	2.72	3.38	0.97	0.06	10.89	3.01	17.78	4.42	8.32	9.78	11.29

CDINL=0.0   CDAFT=0.0   CDPROT=0.0

CDO3=0.2912   CDOW=0.0705   CDOT=0.0307   CDMISC=0.0292   CDOWBT=0.3924

VXM= 2.50 DELTA= 0.0

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	-0.56	0.39	-0.18	-0.09	-0.15	-0.06	-0.09	0.02	-0.18	-0.15	0.00	0.00	-0.58	0.37	17.78	4.42	3.38	10.50	-0.19
0.	0.00	0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	17.78	4.42	-0.00	8.27	0.00
2.	0.56	0.39	0.18	0.09	0.15	0.06	0.09	0.02	0.18	0.15	0.00	0.00	0.58	0.37	17.78	4.42	3.38	10.50	0.19
4.	1.31	0.47	0.47	0.18	0.31	0.11	0.25	0.09	0.47	0.31	0.00	0.00	1.34	0.37	17.78	4.42	5.09	11.03	-0.27
6.	2.17	0.63	0.79	0.27	0.47	0.17	0.48	0.25	0.80	0.47	0.00	0.00	2.21	0.40	17.78	4.42	6.14	11.23	-0.91
8.	3.14	0.91	1.14	0.35	0.64	0.22	0.79	0.53	1.15	0.64	0.00	0.00	3.19	0.46	17.78	4.42	6.86	11.32	-1.61
10.	4.21	1.34	1.51	0.44	0.81	0.28	1.18	0.96	1.51	0.81	0.00	0.00	4.27	0.59	17.78	4.42	7.40	11.37	-2.34
12.	5.39	1.98	1.89	0.52	0.98	0.33	1.68	1.60	1.89	0.98	0.00	0.00	5.47	0.81	17.78	4.42	7.82	11.38	-3.06
14.	6.70	2.87	2.27	0.60	1.16	0.38	2.29	2.49	2.28	1.15	0.00	0.00	6.80	1.16	17.78	4.42	8.16	11.37	-3.73
16.	8.14	4.09	2.67	0.68	1.34	0.43	3.03	3.71	2.67	1.33	0.00	0.00	8.28	1.69	17.78	4.42	8.44	11.34	-4.32

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.2796 CDOW=0.0682 CDOT=0.0297 CDMISC=0.0296 CDOWBT=0.3776

VXM= 2.50 DELTA= 10.00

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	0.14	0.39	-0.13	-0.09	0.24	0.21	-0.09	0.00	-0.13	0.24	0.45	0.01	0.13	0.40	17.78	4.42	3.38	*****	3.56
0.	0.81	0.42	0.00	0.00	0.54	0.27	0.00	0.03	0.00	0.54	0.44	0.01	0.81	0.42	17.78	4.42	-0.00	4.58	5.04
2.	1.36	0.47	0.13	0.09	0.72	0.32	0.09	0.08	0.13	0.72	0.44	0.01	1.37	0.42	17.78	4.42	3.38	6.60	5.77
4.	2.14	0.60	0.43	0.18	0.91	0.38	0.25	0.21	0.43	0.91	0.44	0.01	2.17	0.45	17.78	4.42	5.09	8.31	5.43
6.	3.04	0.84	0.76	0.27	1.10	0.43	0.48	0.45	0.77	1.11	0.43	0.01	3.08	0.51	17.78	4.42	6.14	9.22	4.92
8.	4.03	1.20	1.12	0.35	1.29	0.48	0.79	0.81	1.12	1.30	0.43	0.01	4.08	0.62	17.78	4.42	6.86	9.76	4.33
10.	5.13	1.73	1.49	0.44	1.49	0.53	1.18	1.34	1.49	1.50	0.42	0.01	5.19	0.81	17.78	4.42	7.40	10.11	3.70
12.	6.33	2.47	1.87	0.52	1.68	0.58	1.68	2.08	1.87	1.69	0.42	0.01	6.41	1.10	17.78	4.42	7.82	10.34	3.06
14.	7.65	3.47	2.26	0.60	1.87	0.63	2.29	3.08	2.26	1.88	0.41	0.01	7.76	1.52	17.78	4.42	8.16	10.50	2.45
16.	9.10	4.82	2.66	0.68	2.06	0.67	3.03	4.43	2.66	2.07	0.40	0.01	9.25	2.13	17.78	4.42	8.44	10.62	1.89

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.2796 CDOW=0.0682 CDOT=0.0297 CDMISC=0.0296 CDOWBT=0.3776

VXM= 2.50 DELTA= 20.00

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	0.61	0.44	-0.08	-0.09	0.41	0.46	-0.09	0.02	-0.08	0.41	0.84	0.05	0.59	0.46	17.78	4.42	3.38	1.18	5.70
0.	1.69	0.55	0.00	0.00	1.19	0.51	0.00	0.13	0.00	1.19	0.83	0.04	1.69	0.55	17.78	4.42	-0.00	4.57	10.59
2.	2.20	0.63	0.08	0.09	1.39	0.56	0.09	0.21	0.08	1.39	0.82	0.04	2.22	0.56	17.78	4.42	3.38	5.51	11.77
4.	2.98	0.82	0.37	0.18	1.59	0.60	0.25	0.40	0.37	1.59	0.81	0.04	3.02	0.61	17.78	4.42	5.09	6.99	11.55
6.	3.90	1.13	0.72	0.27	1.78	0.65	0.48	0.71	0.73	1.80	0.80	0.04	3.95	0.71	17.78	4.42	6.14	8.05	10.94
8.	4.91	1.57	1.08	0.35	1.98	0.70	0.79	1.15	1.09	2.00	0.78	0.04	4.97	0.87	17.78	4.42	6.86	8.75	10.29
10.	6.00	2.18	1.46	0.44	2.18	0.74	1.18	1.76	1.47	2.20	0.77	0.04	6.08	1.10	17.78	4.42	7.40	9.24	9.60
12.	7.20	3.00	1.85	0.52	2.36	0.78	1.68	2.59	1.85	2.39	0.75	0.04	7.29	1.44	17.78	4.42	7.82	9.60	8.88
14.	8.50	4.10	2.24	0.60	2.55	0.82	2.29	3.68	2.25	2.58	0.74	0.03	8.63	1.92	17.78	4.42	8.16	9.88	8.15
16.	9.93	5.53	2.64	0.68	2.72	0.86	3.03	5.12	2.64	2.75	0.72	0.03	10.10	2.58	17.78	4.42	8.44	10.08	7.45

CDINL=0.0   CDAFT=0.0   CDPROT=0.0

CDOB=0.2796   CDOW=0.0682   CDOT=0.0297   CDMISC=0.0296   CDOWBT=0.3776

VXM= 2.50 . DELTA= 30.00

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	0.69	0.48	-0.14	-0.09	0.38	0.64	-0.09	0.02	-0.15	0.37	1.14	0.08	0.68	0.51	17.78	4.42	3.38	0.43	7.03
0.	2.50	0.73	0.00	0.00	1.82	0.68	0.00	0.27	0.00	1.82	1.12	0.08	2.50	0.73	17.78	4.42	-0.00	4.55	15.67
2.	3.06	0.87	0.14	0.09	2.01	0.72	0.09	0.41	0.15	2.02	1.10	0.08	3.08	0.76	17.78	4.42	3.38	5.52	16.33
4.	3.66	1.05	0.27	0.18	2.20	0.77	0.25	0.60	0.28	2.21	1.07	0.07	3.70	0.79	17.78	4.42	5.09	6.20	17.12
6.	4.60	1.41	0.67	0.27	2.38	0.80	0.48	0.97	0.67	2.41	1.05	0.07	4.66	0.93	17.78	4.42	6.14	7.36	16.11
8.	5.59	1.90	1.05	0.35	2.55	0.84	0.79	1.46	1.05	2.59	1.02	0.07	5.66	1.11	17.78	4.42	6.86	8.14	15.18
10.	6.66	2.56	1.43	0.44	2.72	0.88	1.18	2.12	1.44	2.77	0.99	0.06	6.75	1.37	17.78	4.42	7.40	8.71	14.23
12.	7.82	3.43	1.83	0.52	2.88	0.91	1.68	3.00	1.83	2.93	0.96	0.06	7.94	1.73	17.78	4.42	7.82	9.15	13.23
14.	9.08	4.56	2.23	0.60	3.02	0.94	2.29	4.13	2.23	3.08	0.93	0.06	9.23	2.23	17.78	4.42	8.16	9.50	12.21
16.	10.47	6.03	2.63	0.68	3.16	0.97	3.03	5.60	2.63	3.22	0.90	0.05	10.66	2.91	17.78	4.42	8.44	9.77	11.18

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.2796 CDOW=0.0682 CDOT=0.0297 CDMISC=0.0296 CDOWBT=0.3776

VXM= 3.00 DELTA= 10.00

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	0.12	0.38	-0.13	-0.07	0.22	0.20	-0.09	0.00	-0.14	0.22	0.42	0.01	0.11	0.38	17.78	4.42	3.38	*****	3.25
0.	0.76	0.40	0.00	0.00	0.51	0.25	0.00	0.03	0.00	0.51	0.41	0.01	0.76	0.40	17.78	4.42	-0.00	4.66	4.68
2.	1.28	0.45	0.13	0.07	0.68	0.30	0.09	0.07	0.14	0.68	0.41	0.01	1.29	0.40	17.78	4.42	3.38	6.68	5.36
4.	2.03	0.57	0.42	0.15	0.86	0.35	0.25	0.19	0.42	0.86	0.41	0.01	2.05	0.43	17.78	4.42	5.10	8.34	5.09
6.	2.89	0.78	0.74	0.22	1.04	0.40	0.49	0.41	0.74	1.05	0.40	0.01	2.92	0.48	17.78	4.42	6.17	9.23	4.66
8.	3.85	1.12	1.08	0.29	1.23	0.44	0.81	0.75	1.09	1.23	0.40	0.01	3.90	0.57	17.78	4.42	6.92	9.75	4.16
10.	4.93	1.63	1.44	0.37	1.41	0.49	1.23	1.26	1.44	1.42	0.39	0.01	4.99	0.75	17.78	4.42	7.48	10.09	3.63
12.	6.14	2.37	1.81	0.43	1.60	0.53	1.77	1.99	1.81	1.60	0.39	0.01	6.22	1.04	17.78	4.42	7.93	10.32	3.12
14.	7.50	3.41	2.18	0.50	1.78	0.57	2.47	3.03	2.18	1.78	0.38	0.01	7.62	1.49	17.78	4.42	8.29	10.47	2.66
16.	9.88	5.78	2.57	0.57	1.96	0.61	4.18	5.41	2.56	1.96	0.38	0.01	10.07	2.84	17.78	4.42	8.86	10.52	3.01

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.2688 CDOW=0.0664 CDOT=0.0289 CDMISC=0.0301 CDOWBT=0.3642

VXM= 3.00 DELTA= 20.00

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	0.53	0.42	-0.09	-0.07	0.36	0.43	-0.09	0.01	-0.09	0.36	0.79	0.04	0.52	0.44	17.78	4.42	3.38	0.97	5.10
0.	1.60	0.51	0.00	0.00	1.13	0.47	0.00	0.11	0.00	1.13	0.78	0.04	1.60	0.51	17.78	4.42	-0.00	4.63	9.90
2.	2.03	0.59	0.09	0.07	1.32	0.52	0.09	0.19	0.09	1.32	0.77	0.04	2.10	0.52	17.78	4.42	3.38	5.59	11.00
4.	2.84	0.77	0.37	0.15	1.51	0.56	0.25	0.37	0.37	1.52	0.75	0.04	2.87	0.57	17.78	4.42	5.10	7.03	10.85
6.	3.71	1.05	0.70	0.22	1.70	0.60	0.49	0.65	0.71	1.71	0.74	0.04	3.76	0.65	17.78	4.42	6.17	8.07	10.34
8.	4.69	1.46	1.05	0.29	1.89	0.64	0.81	1.06	1.06	1.91	0.73	0.03	4.75	0.79	17.78	4.42	6.92	8.76	9.80
10.	5.76	2.04	1.42	0.37	2.07	0.68	1.23	1.65	1.42	2.10	0.72	0.03	5.84	1.01	17.78	4.42	7.48	9.24	9.22
12.	6.97	2.86	1.79	0.43	2.25	0.72	1.77	2.47	1.79	2.28	0.70	0.03	7.06	1.35	17.78	4.42	7.93	9.60	8.63
14.	8.32	3.99	2.17	0.50	2.43	0.76	2.47	3.60	2.17	2.45	0.68	0.03	8.45	1.86	17.78	4.42	8.29	9.87	8.07
16.	10.68	6.52	2.56	0.57	2.59	0.79	4.18	6.13	2.55	2.62	0.67	0.03	10.89	3.32	17.78	4.42	8.86	10.06	8.28

CDINL=0.0 CDAFT=0.0 CDPROT=0.0

CDOB=0.2688 CDOW=0.0664 CDOT=0.0289 CDMISC=0.0301 CDOWBT=0.3642

VXM= 3.00 DELTA= 30.00

AL	CLTOT	CDTOT	CLWP	CLBW	CLTP	CLBT	CLB	CDI	CNWP	CNTP	CLTD	CDTD	CN	CA	XCPW	XCPT	XCPB	XCP	CM
-2.	0.59	0.45	-0.15	-0.07	0.31	0.60	-0.09	0.02	-0.15	0.31	1.07	0.07	0.58	0.47	17.78	4.42	3.38	0.20	6.14
0.	2.38	0.68	0.00	0.00	1.74	0.64	0.00	0.25	0.00	1.74	1.05	0.07	2.38	0.68	17.78	4.42	-0.00	4.61	14.75
2.	2.91	0.80	0.15	0.07	1.92	0.67	0.09	0.37	0.15	1.93	1.02	0.07	2.93	0.70	17.78	4.42	3.38	5.57	15.38
4.	3.50	0.98	0.28	0.15	2.10	0.71	0.25	0.55	0.29	2.12	1.00	0.06	3.53	0.73	17.78	4.42	5.10	6.26	16.12
6.	4.39	1.31	0.66	0.22	2.28	0.74	0.49	0.88	0.66	2.30	0.98	0.06	4.44	0.84	17.78	4.42	6.17	7.38	15.26
8.	5.34	1.77	1.02	0.29	2.44	0.78	0.81	1.35	1.03	2.48	0.95	0.06	5.42	1.01	17.78	4.42	6.92	8.15	14.45
10.	6.40	2.40	1.39	0.37	2.60	0.81	1.23	1.98	1.40	2.65	0.92	0.05	6.49	1.25	17.78	4.42	7.48	8.72	13.63
12.	7.57	3.26	1.77	0.43	2.75	0.84	1.77	2.85	1.77	2.80	0.90	0.05	7.68	1.62	17.78	4.42	7.93	9.16	12.78
14.	8.88	4.43	2.15	0.50	2.89	0.87	2.47	4.02	2.15	2.94	0.87	0.05	9.03	2.15	17.78	4.42	8.29	9.50	11.93
16.	11.20	7.03	2.54	0.57	3.02	0.89	4.18	6.62	2.54	3.07	0.84	0.05	11.43	3.67	17.78	4.42	8.86	9.78	11.84

CDINL=0.0   CDAFT=0.0   CDPROT=0.0

CDOB=0.2688   CDOW=0.0664   CDOT=0.0289   CDMISC=0.0301   CDOWBT=0.3642

X. CONCLUSIONS AND RECOMMENDATIONS

This thesis has presented the methods and general procedures for the conceptual design of tactical missiles. As mentioned, this is not necessarily the best design. Now that the design procedure has been attempted once, the reason for this is readily seen. The process is one of continuous compromise. As was shown in Chapter 7, the optimum wing for lift is not the best wing for minimizing drag. We also saw in Chapter 8 that increasing chamber pressure increases thrust at the expense of increased weight. This thesis has tried to point out some of these areas of compromise and present methods to deal with them.

Areas which were not covered which need to be investigated in conceptual design are structures, radar cross-section and cost. With the increased emphasis on survivability and the decreasing budget, it becomes increasingly important to define the effects of these areas on design early in the process.

The complexity of the design process and the need to obtain timely and accurate information have made it ideally suited for the digital computer. The AEROCF program used in this thesis is part of a large scale computer program (MISSYN) which consists of modules for each section of the design analysis.

With a good understanding of the theory and methods used in missile design, the computer aided design program with graphics capability gives the designer the capacity to make intelligent design interations and almost instantaneously see the effect of the change on all areas of design. A limited example of this can be seen in the use of AERO1. A change in the performance requirements for maneuver capability would require a redesign of the lifting surfaces. A change in the lifting surface design would change the drag characteristics of the missile and therefore, the propulsion requirements. The AERO1 program coupled with a similar propulsion module would allow the designer to make the changes and instantly see the penalty or savings in propellant weight.

One pass at the design has been accomplished in this thesis. As was seen throughout the process, decisions in one area affect the design in others. For this reason the design process becomes an iterative one. The final design of the first iteration is the baseline missile for the second iteration and the design is started again. By making several passes through the loop, the solution converges on the final design.

```
      SUBROUTINE GEOSUB                                                 AER00010
      DIMENSION XVXM(16),XDT(16),XAL(48)                                AER00020
      COMMON REFT,SSUBS,XLOB,ZF,VXM,IZZY,LLKK,LLLL,NSURF                AER00030
      COMMON ICSC,INOSE,ISWPW,IAFBW,ISWPW2,IAFBW2,ISWPT,IAFBT,IDUM1,    AER00040
     1CLAMT,CLAMW,CLAMW2,D,XLNOSE,BT,BW,BW2,CROOTW,CROOTT,CROOW2,       AER00050
     2ST,SW,SW2,TOVCW,TOVCW2,TOVCT,XLAMT,XLAMW,XLAMW2,                  AER00060
     3XMACW,XMACW2,XMACT,XWING,XWING2,XTAIL,HT,XL,AREA,XREF,            AER00070
     4ISWEPW,ISWEPT,ISWEP2,NWING,NTAIL,NWING2,ENGINE,ENLET,BETA,DBASE,  AER00080
     5DJET,XLABOD                                                       AER00090
      COMMON ART,ARW,ARW2,BAR,BCOLAM,BETA1,B1,CLALT,CLALW,CLALW2,CLAL1, AER00100
     1COLAM,CROOT,IAFB,ISWP,TOVC,ODC,XBCRBW,XBCRWB,XKBT,XKBW,XKTB,XKTBT,AER00110
     2XKWB,XKWBI,ISWP1,RATIO,XLAM1,XMAC,D1                              AER00120
      DRAT=XLNOSE/D                                                     AER00130
      DRAA=XLABOD/D                                                     AER00140
      D1=D                                                              AER00150
      XLOB=XL/D                                                         AER00160
      IF(CLAMW-5.) 10,10,20                                             AER00170
 10   CLAMW=5.                                                          AER00180
   20 IF(CLAMW2-5.) 30,30,40                                            AER00190
   30 CLAMW2=5.                                                         AER00200
   40 IF(CLAMT-5.) 50,50,60                                             AER00210
   50 CLAMT=5.                                                          AER00220
   60 CONTINUE                                                          AER00230
      CLAMW=CLAMW/57.29578                                              AER00240
      CLAMT=CLAMT/57.29578                                              AER00250
      CLAMW2=CLAMW2/57.29578                                            AER00260
      IF (INOSE-1) 1571,1572,1571                                       AER00270
 1572 SS1=(3.14*DRAT)+0.4                                               AER00280
      GO TO 1579                                                        AER00290
 1571 IF(INOSE-2) 1573,1574,1573                                        AER00300
 1574 SS1=(2.68*DRAT)+0.1                                               AER00310
      GO TO 1579                                                        AER00320
 1573 IF(INOSE-3) 1579,1576,1579                                        AER00330
 1576 SS1=(2.0*DRAT)+.2                                                 AER00340
 1579 SSUBS=3.14159*D*(XL-XLNOSE-XLABOD)+(SS1+2.68*DRAA*0.9)*(3.14159*D*AER00350
     1D/4.0)                                                            AER00360
      WRITE(6,9111)SSUBS                                                AER00370
 9111 FORMAT(/,1X,'NOSE WETTED AREA = ',F10.4,/)                        AER00380
      IF(DRAT-.6) 1580,1580,1581                                        AER00390
 1580 ZF=1.                                                             AER00400
      GO TO 1594                                                        AER00410
 1581 ZF=1.522*EXP(-.7*DRAT)                                            AER00420
 1594 Z=HT*0.001                                                        AER00430
      IF(HT-35332.0) 1595,1595,1596                                     AER00440
 1595 T=519.-HT/128.                                                    AER00450
      PS=(1.91-0.01315*Z)**5.256                                        AER00460
      GO TO 1597                                                        AER00470
 1596 T=393.                                                            AER00480
```

```
      B=1.69-0.0478*Z
      PS=6.49*EXP(B)
 1597 C=49.1*SQRT(T)
      PS=PS*70.9
      RHO=PS/(1715.*T)
      XMU=2.270*(T**1.5)/((T+198.6)*(10.**8))
      REFT=(C*RHO)/XMU
      WRITE(6,80000)
80000 FORMAT(/,1X,'IS THIS PROGRAM COMPARING EXPERIMENTAL DATA')
      WRITE(6,80001)
80001 FORMAT(1X,'ENTER  0=NO, 1=YES')
      READ 1112,IEXP
 1112 FORMAT(I2)
      IF(IEXP.EQ.0)GO TO 80500
      WRITE(6,80100)
80100 FORMAT(/,1X,'ENTER RE/M/XREF OF EXPERIMENTAL DATA')
      READ 1113, REFT
 1113 FORMAT(F12.2)
80500 CONTINUE
      RETURN
      END
C
C
C
      SUBROUTINE CLASUB
      DIMENSION XVXM(16),XDT(16),XAL(48)
      COMMON REFT,SSUBS,XLOB,ZF,VXM,IZZY,LLKK,LLLL,NSURF
      COMMON ICSC,INOSE,ISWPW,IAFBW,ISWPW2,IAFBW2,ISWPT,IAFBT,IDUM1,
     1CLAMT,CLAMW,CLAMW2,D,XLNOSE,BT,BW,BW2,CROOTW,CROOTT,CROOW2,
     2ST,SW,SW2,TOVCW,TOVCW2,TOVCT,XLAMT,XLAMW,XLAMW2,
     3XMACW,XMACW2,XMACT,XWING,XWING2,XTAIL,HT,XL,AREA,XREF,
     4ISWEPW,ISWEPT,ISWEP2,NWING,NTAIL,NWING2,ENGINE,ENLET,BETA,DBASE,
     5DJET,XLABOD
      COMMON ART,ARW,ARW2,BAR,BCOLAM,BETA1,B1,CLALT,CLALW,CLALW2,CLAL1,
     1COLAM,CROOT,IAFB,ISWP,TOVC,ODC,XBCRBW,XBCRWB,XKBT,XKBW,XKTB,XKTBT,
     2XKWB,XKWBI,ISWP1,RATIO,XLAM1,XMAC,D1
      IF (VXM-1.)2,2,3
    2 BETA1=SQRT (1.-VXM**2)
      GO TO 4
    3 BETA1=SQRT (VXM**2-1.)
    4 IF(IZZY-4)902,902,1111
 1111 IF(VXM-1.)41,42,41
   42 BETA1=0.0000001
   41 KFIN=0
      KFIN=KFIN+1
      IF (SW) 504,504,411
  411 ARW = (BW - D)**2/SW
      BAR=BETA1*ARW
```

```
      ISWP=ISWPW                                                          AER00970
      XLAM=XLAMW                                                          AER00980
      AR=ARW                                                              AER00990
  505 IF(BAR.GT.5.0.AND.VXM.GE.1.0)  BAR=5.0                              AER01000
      IF(BAR.GT.5.0.AND.VXM.LT.1.0)  BAR=5.0                              AER01010
      IF(ISWP-1) 5,5,200                                                  AER01020
    5 IF(XLAM-.25) 60,10,10                                               AER01030
   10 IF(VXM-1.0) 20,20,30                                                AER01040
   20 CLAR=-.1833*BAR+1.6                                                 AER01050
      GO TO 370                                                           AER01060
   30 IF(XLAM-.50)40,110,50                                               AER01070
   40 CLAR=-.00103251 8*BAR**8+.0200677*BAR**7-.1557225*BAR**6            AER01080
     1+.607131*BAR**5-1.21537*BAR**4+1.13786*BAR**3-.5718*BAR**2          AER01090
     1+.458487*BAR+1.57588                                                AER01100
      GO TO 370                                                           AER01110
  110 CLAR=.00121006*BAR**8-.0254597*BAR**7+.22119793*BAR**6              AER01120
     1- 1.020448*BAR**5+2.651997*BAR**4-3.6809957*BAR**3                  AER01130
     1 +1.97903*BAR**2+.27640134*BAR+1.57129                              AER01140
      GO TO 370                                                           AER01150
   50 CLAR=-.00007776*BAR**8-.001814086*BAR**7+.051777483*BAR**6          AER01160
     1-.43555555*BAR**5+1.7240831*BAR**4-3.3472653*BAR**3                 AER01170
     1+2.6137236*BAR**2-.23389542*BAR+1.57998                             AER01180
      GO TO 370                                                           AER01190
   60 IF(VXM-1.) 70,70,80                                                 AER01200
   70 CLAR=-.1667*BAR+1.575                                               AER01210
      GO TO 370                                                           AER01220
   80 IF(BAR-2.)90,90,100                                                 AER01230
  100 CLAR=.00133364*BAR**5-.0318237*BAR**4+.26049*BAR**3-.8643*BAR**2    AER01240
     1+.669396*BAR+2.2008                                                 AER01250
      GO TO 370                                                           AER01260
   90 CLAR=-.040277*BAR**4+.222522*BAR**3-.48931*BAR**2+.47287*BAR+1.57   AER01270
      GO TO 370                                                           AER01280
  200 IF (XLAM-.1) 210,260,260                                            AER01290
  210 IF(VXM-1.) 220,220,230                                              AER01300
  220 CLAR=-.2077*BAR+1.575                                               AER01310
      GO TO 370                                                           AER01320
  230 IF(BAR-.25) 240,240,250                                             AER01330
  240 CLAR=.2077*BAR+1.575                                                AER01340
      GO TO 370                                                           AER01350
  250 IF(BAR-4.) 251,251,252                                              AER01360
  251 CLAR=-.1668*BAR+1.667                                               AER01370
      GO TO 370                                                           AER01380
  252 CLAR=1.587*(1.26)**(2.-BAR)                                         AER01390
      GO TO 370                                                           AER01400
  260 IF (XLAM-.3) 270,320,320                                            AER01410
  270 IF(VXM-1.) 280,280,290                                              AER01420
  280 CLAR=-.2065*BAR+1.6                                                 AER01430
      GO TO 370                                                           AER01440
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290 CLAR=.002119027*BAR**5-.03283282*BAR**4+.20366375*BAR**3           AER01450
   1-.61820362*BAR**2+.62703849*BAR+1.550048                            AER01460
    GO TO 370                                                          AER01470
320 IF(VXM-1.) 330,330,340                                             AER01480
330 CLAR=-.225*BAR+1.675                                               AER01490
    GO TO 370                                                          AER01500
340 IF(XLAM.LE..40)CLAR=.00070428*BAR**8-.0158837*BAR**7               AER01510
   1+.1489347*BAR**6-.74733673*BAR**5+2.1861823*BAR**4                  AER01520
   1-3.3445976*BAR**3+2.2919403*BAR**2-.21045286*BAR+1.6203524          AER01530
    IF(XLAM.GT..40)CLAR=-.00012278513*BAR**8+.0000879756*BAR**7        AER01540
   1+.025071933*BAR**6-.25587433*BAR**5+1.0834904*BAR**4                AER01550
   1-2.1562044*BAR**3+1.6307710*BAR**2-.084287165*BAR+1.7039            AER01560
370 CLAL=CLAR*AR                                                       AER01570
    IF (KFIN-2) 500,501,502                                            AER01580
500 CLALW=CLAL                                                         AER01590
    GO TO 503                                                          AER01600
501 CLALW2=CLAL                                                        AER01610
    GO TO 503                                                          AER01620
502 CLALT=CLAL                                                         AER01630
503 IF (KFIN-2) 504,507,900                                            AER01640
504 KFIN=KFIN+1                                                        AER01650
    IF (SW2) 507,507,506                                               AER01660
506 AR=(BW2-D)**2/SW2                                                  AER01670
    BAR=BETA1*AR                                                       AER01680
    ISWP=ISWPW2                                                        AER01690
    ARW2=AR                                                            AER01700
    XLAM=XLAMW2                                                        AER01710
    GO TO 505                                                          AER01720
507 KFIN=KFIN+1                                                        AER01730
    IF (ST) 509,509,508                                                AER01740
508 AR=(BT-D)**2/ST                                                    AER01750
    BAR=BETA1*AR                                                       AER01760
    ART=AR                                                             AER01770
    ISWP=ISWPT                                                         AER01780
    NSURF=NTAIL                                                        AER01790
    XLAM=XLAMT                                                         AER01800
    GO TO 505                                                          AER01810
509 IF (SW) 5100,5100,900                                              AER01820
5100 IF (SW2) 5110,5110,900                                            AER01830
5110 IF (ST) 980,980,900                                               AER01840
980 LLLL=2                                                             AER01850
    RETURN                                                             AER01860
900 LLKK=0                                                             AER01870
902 IZZY = IZZY + 1                                                    AER01880
    IF (SW) 510,510,901                                                AER01890
901 COLAM= COS(CLAMW)/(SIN(CLAMW+.1))                                  AER01900
    ARW=(BW-D)**2/SW                                                   AER01910
    BCOLAM=BETA1*COLAM                                                 AER01920
```

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      CROOT=CROOTW                                                      AER01930
      B1=BW                                                             AER01940
      IAFB=IAFBW                                                        AER01950
      XMAC=XMACW                                                        AER01960
      TOVC=TOVCW                                                        AER01970
      CLAL1=CLALW                                                       AER01980
      XLAM1=XLAMW                                                       AER01990
      ISWP1=ISWPW                                                       AER02000
      NSURF=NWING                                                       AER02010
      BAR=BETA1*ARW                                                     AER02020
      RATIO=CROOT/(BETA1*D)                                             AER02030
      LLLL=0                                                            AER02040
      RETURN                                                            AER02050
  510 IZZY =  IZZY + 1                                                  AER02060
      IF (SW2) 942,942,511                                              AER02070
  942 LLLL=1                                                            AER02080
      RETURN                                                            AER02090
  511 COLAM=COS(CLAMW2)/(SIN(CLAMW2+.1))                                AER02100
      BCOLAM=BETA1*COLAM                                                AER02110
      CROOT=CROOW2                                                      AER02120
      B1=BW2                                                            AER02130
      IAFB=IAFBW2                                                       AER02140
      CLAL1=CLALW2                                                      AER02150
      XLAM1=XLAMW2                                                      AER02160
      NSURF=NWING2                                                      AER02170
      XMAC=XMACW2                                                       AER02180
      TOVC=TOVCW2                                                       AER02190
      ISWP1=ISWPW2                                                      AER02200
      ARW2=(BW2-D)**2/SW2                                               AER02210
      BAR=BETA1*ARW2                                                    AER02220
      RATIO=CROOT/(BETA1*D)                                             AER02230
      LLLL=0                                                            AER02240
      RETURN                                                            AER02250
      END                                                               AER02260
C                                                                       AER02270
C                                                                       AER02280
C                                                                       AER02290
      SUBROUTINE CATSUB                                                 AER02300
      DIMENSION XVXM(16),XDT(16),XAL(48)                                AER02310
      COMMON REFT,SSUBS,XLOB,ZF,VXM,IZZY,LLKK,LLLL,NSURF                AER02320
      COMMON ICSC,INOSE,ISWPW,IAFBW,ISWPW2,IAFBW2,ISWPT,IAFBT,IDUM1,    AER02330
     1CLAMT,CLAMW,CLAMW2,D,XLNOSE,BT,BW,BW2,CROOTW,CROOTT,CROOW2,       AER02340
     2ST,SW,SW2,TOVCW,TOVCW2,TOVCT,XLAMT,XLAMW,XLAMW2,                  AER02350
     3XMACW,XMACW2,XMACT,XWING,XWING2,XTAIL,HT,XL,AREA,XREF,            AER02360
     4ISWEPW,ISWEPT,ISWEP2,NWING,NTAIL,NWING2,ENGINE,ENLET,BETA,DBASE,  AER02370
     5DJET,XLABOD                                                       AER02380
      COMMON ART,ARW,ARW2,BAR,BCOLAM,BETA1,B1,CLALT,CLALW,CLALW2,CLAL1, AER02390
     1COLAM,CROOT,IAFB,ISWP,TOVC,ODC,XBCRBW,XBCRWB,XKBT,XKBW,XKTB,XKTBT,AER02400
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     2XKWB,XKWBI,ISWP1,RATIO,XLAM1,XMAC,D1                              AER02410
      XKWB=(2./3.14159)*((1.+D**4/B1**4)*(.5*ATAN(.5*(B1/D-D/B1))+3.1415AER02420
     19/4.)-(D**2/B1**2)*((B1/D-D/B1)+2.*ATAN(D/B1)))/(1.-D/B1)**2      AER02430
  926 XKTB1=((3.14159)**2*D**2*(B1/D+1.)**2)/(4.*B1**2)+(3.14159*D**2*(BAER02440
     11**2/D**2+1.)**2/(B1**2*(B1/D-1.)**2))*ARSIN((B1**2/D**2-1.)/(B1**AER02450
     22/D**2+1.))                                                       AER02460
      XKTB2=2.*3.14159*D*(B1/D+1.)/(B1*(B1/D-1.))-((B1**2/D**2+1.)**2/((AER02470
     1B1**2/D**2)*(B1/D-1.)**2))*(ARSIN((B1**2/D**2-1.)/(B1**2/D**2+1.))AER02480
     2)**2                                                              AER02490
      XKTB3=(4.*D*(B1/D+1.)/(B1*(B1/D-1.)))*ARSIN((B1**2/D**2-1.)/(B1**2AER02500
     1/D**2+1.))-(8./(B1/D-1.)**2)*ALOG10((B1**2/D**2+1.)/(2.*B1/D))    AER02510
      XKTB=(1./(3.14159)**2)*(XKTB1-XKTB2-XKTB3)                        AER02520
      IF (ICSC-1) 970,970,971                                           AER02530
  970 IF (LLKK) 972,972,973                                             AER02540
  972 XKWBI=D/B1+1.                                                     AER02550
      XKTBI=XKTB                                                        AER02560
      GO TO 973                                                         AER02570
  971 IF (LLKK-1) 973,973,972                                           AER02580
  973 BAREF=BAR*(1.+XLAM1)*((1./(BETA1*COLAM))+1.)                      AER02590
      IF (BAREF-4.) 928,928,929                                         AER02600
  928 XKBW=(1.+D/B1)**2-XKWB                                            AER02610
      GO TO 1000                                                        AER02620
  929 IF (IAFB) 9291,9292,9291                                          AER02630
 9291 IF (BCOLAM-1.) 932,931,931                                        AER02640
  931 XKBW1=(BCOLAM/(1.+BCOLAM))*((((BCOLAM+1.)*(1./RATIO)+BCOLAM)/BCOLAAER02650
     1M)**2)*ARCOS((1.+(1.+BCOLAM)*(1./RATIO))/(BCOLAM+(BCOLAM+1.)*(1./ AER02660
     2RATIO)))                                                          AER02670
      XKBW2=(SQRT(BCOLAM**2-1.)/(BCOLAM+1.))*(SQRT(1.+2.*BETA1*D/CROOT)-AER02680
     11.)-(SQRT(BCOLAM**2-1.)/BCOLAM)*(BETA1*D/CROOT)**2*ALOG((1.+CROOT/AER02690
     2(BETA1*D))+SQRT((1.+CROOT/(BETA1*D))**2-1.))-(BCOLAM/(1.+BCOLAM))*AER02700
     3ARCOS(1./BCOLAM)                                                  AER02710
      XKBW=(8.*BCOLAM/(3.14159*SQRT(BCOLAM**2-1.)*(1.+XLAM1)*(BETA1*D/  AER02720
     1CROOT)*(B1/D-1.)*(BETA1*CLAL1)))*(XKBW1+XKBW2)                    AER02730
      GO TO 1000                                                        AER02740
  932 XKBW1=((BCOLAM+(1.+BCOLAM)*BETA1*D/CROOT)/BCOLAM)**1.5+((BCOLAM+(1AER02750
     1.+BCOLAM)*BETA1*D/CROOT)/BCOLAM)**.5-2.                           AER02760
      XKBW2=(((1.+BCOLAM)*BETA1*D/CROOT)/BCOLAM)**2*0.5*(ALOG(1.+SQRT(BCAER02770
     1OLAM/(BCOLAM+(1.+BCOLAM)*BETA1*D/CROOT)))-ALOG(1.-SQRT(BCOLAM/(BCOAER02780
     2LAM+(1.+BCOLAM)*BETA1*D/CROOT))))                                 AER02790
      XKBW=(16.*(BCOLAM/(1.+BCOLAM))**2/(3.14159*(1.+XLAM1)*(BETA1*D/   AER02800
     1CROOT)*(B1/D-1.)*(BETA1*CLAL1)))*(XKBW1-XKBW2)                    AER02810
      GO TO 1000                                                        AER02820
 9292 IF(BCOLAM-1.) 9295,9294,9294                                      AER02830
 9294 IF(RATIO-1.) 9293,9311,9311                                       AER02840
 9293 RATIO=1.                                                          AER02850
      D=CROOT/BETA1                                                     AER02860
 9311 XKB1=(1.+COLAM*BETA1*RATIO)**2*ARCOS((BCOLAM+RATIO)/(1.+COLAM*BETAAER02870
     11*RATIO))                                                         AER02880
```

```
      XKB2=BCOLAM**2*RATIO**2*ARCOS(1./BCOLAM)-BCOLAM*RATIO**2*SQRT(BCOLAER02890
     1AM**2-1.)*ARSIN(1./RATIO)                                         AER02900
      XKB3=SQRT(BCOLAM**2-1.)*ALOG( RATIO+SQRT(RATIO**2-1.))            AER02910
      XKBW=((8./(3.14159*SQRT(BCOLAM**2-1.)*BETA1*CLAL1*(XLAM1+1.)*(B1/DAER02920
     11-1.)))*(1./RATIO))*(XKB1-XKB2-XKB3)                              AER02930
      GO TO 1000                                                        AER02940
 9295 IF(RATIO-1.) 9296,9312,9312                                       AER02950
 9296 RATIO=1.                                                          AER02960
        D=CROOT/BETA1                                                   AER02970
 9312 XKB1=(1.+COLAM*BETA1*RATIO)*SQRT((RATIO-1.)*(COLAM*BETA1*RATIO+1.)AER02980
     1)                                                                 AER02990
      XKB2=RATIO**2*(BCOLAM)**1.5-BCOLAM*RATIO**2*(BCOLAM+1.)*(ATAN(SQRTAER03000
     1(1./BCOLAM))-ATAN(SQRT((RATIO-1.)/(COLAM*BETA1*RATIO+1.))))       AER03010
      XKB3=((BCOLAM+1.)/SQRT(BCOLAM))*0.5*(ALOG(1.+SQRT(BCOLAM*(RATIO-1.AER03020
     1)/(COLAM*BETA1*RATIO+1.)))-ALOG(1.-SQRT(BCOLAM*(RATIO-1.)/(COLAM* AER03030
     2BETA1*RATIO+1.))))                                                AER03040
      XKBW=((16.*SQRT(BCOLAM)*(1./RATIO)/(BETA1*CLAL1*(XLAM1+1.)*(B1/D1 AER03050
     1-1.)*3.14159*(BCOLAM+1.))))*(XKB1-XKB2-XKB3)                      AER03060
 1000 XKBT=XKWB-XKTB                                                    AER03070
      D=D1                                                              AER03080
      IF(VXM-1.0) 2000,2000,2010                                        AER03090
 2000 IF(ISWP1-1   ) 2020,2020,2030                                     AER03100
 2020 IF(BAR-2.0) 2040,2050,2050                                        AER03110
 2040 XBCRWB=0.35-XLAM1*(0.35+17.885-SQRT(328.8782-(BAR-3.)**2))        AER03120
      GO TO 2080                                                        AER03130
 2050 XBCRWB=0.35-0.1*XLAM1                                             AER03140
      GO TO 2080                                                        AER03150
 2030 IF(BAR-2.0) 2060,2070,2070                                        AER03160
 2060 XCR1=SQRT(2029.5+(BAR-3.)**2)                                     AER03170
      XBCRWB=((-44.5+XCR1)-XLAM1*(-44.5+XCR1+17.885-SQRT(328.8782-(BAR  AER03180
     1-3.)**2)))                                                        AER03190
      GO TO 2110                                                        AER03200
 2070 XBCRWB=0.55-0.3*XLAM1                                             AER03210
      GO TO 2110                                                        AER03220
 2080 IF(BAR-4.0) 2090,2100,2100                                        AER03230
 2090 XBCRBW=0.25-XLAM1*(32.125-SQRT(1032.02-(BAR-4.)**2))+(1.-XLAM1)*  AER03240
     1ALOG(1.04+0.1*D/B1)*(-7.5+SQRT( 72.25-(BAR-4.0)**2))              AER03250
      GO TO 2400                                                        AER03260
 2100 XBCRBW=0.25+((1.-XLAM1)*ALOG(1.04+0.1*D/B1))                      AER03270
      GO TO 2400                                                        AER03280
 2110 IF(BAR-4.0) 2120,2130,2130                                        AER03290
 2120 XBCRBW=0.25+(1.-2.*XLAM1)*(32.125-SQRT(1032.02-(BAR-4.)**2))+     AER03300
     1(1.-XLAM1)*ALOG(1.12+0.3*D/B1)*(-7.5+SQRT(72.25-(BAR-4.)**2))     AER03310
      GO TO 2400                                                        AER03320
 2130 XBCRBW=0.25+(1.-XLAM1)*ALOG(1.12+0.3*D/B1)                        AER03330
      GO TO 2400                                                        AER03340
 2010 IF(ISWP1-1   ) 2140,2140,2150                                     AER03350
 2140 IF(BAR-3.0) 2160,2170,2170                                        AER03360
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```
2160 XBCRWB=-(9.235+25.*(1.-XLAM1))+SQRT((9.71+25.*(1.-XLAM1))**2-       AER03370
    1(BAR-3.)**2)                                                        AER03380
     GO TO 2200                                                          AER03390
2170 XBCRWB=0.005*BAR+0.46                                               AER03400
     GO TO 2200                                                          AER03410
2150 IF(BAR-3.) 2180,2190,2190                                           AER03420
2180 XBCRWB=0.675-XLAM1*(0.675+9.235-SQRT(94.1-(BAR-3.)**2))             AER03430
     GO TO 2300                                                          AER03440
2190 XBCRWB=0.005*BAR+0.46+0.2*(1.-XLAM1)                                AER03450
     GO TO 2300                                                          AER03460
2200 BARLAM=BAR*(1.-XLAM1)*(1.+(1./BCOLAM))                              AER03470
     IF(BARLAM-4.0) 2210,2210,2220                                       AER03480
2210 IF(BAR-2.0) 2230,2240,2240                                          AER03490
2230  XBMID1 = ALOG(1.32 - 0.32*XLAM1)                                   AER03500
2235 XBMID2=4.+(XBMID1**2)-((0.5+0.5139*(D/B1)*(1.17+XLAM1)*(1./(0.331 AER03510
    1**(D/B1)))))**2)                                                    AER03520
     XBMID3=2.*((XBMID1)-(0.5+0.5139*(D/B1)*(1.17+XLAM1)*(1./(0.331      AER03530
    1**(D/B1)))))                                                        AER03540
     XBMID=XBMID2/XBMID3                                                 AER03550
     XCMID=4.+(XBMID1-XBMID)**2                                          AER03560
     XBCRBW=SQRT(XCMID-((BAR-2.)**2))+XBMID                              AER03570
     GO TO 2400                                                          AER03580
2240 XBCRBW=0.5+0.25695*(D/B1)*(1./(0.331**(D/B1)))*BAR*(1.17+XLAM1)     AER03590
     GO TO 2400                                                          AER03600
2220 IF(IAFB) 2250,2250,2260                                             AER03610
2250 IF(RATIO-1.0) 2280,2280,2270                                        AER03620
2280 XBCRBW=0.67                                                         AER03630
     GO TO 2400                                                          AER03640
2270 XBCRBW=-2.32+SQRT(8.9401-((1./RATIO)-1.)**2)                        AER03650
     GO TO 2400                                                          AER03660
2260 XBCRBW=(0.429/RATIO)+0.5                                            AER03670
     GO TO 2400                                                          AER03680
2300 BARLAM=BAR*(1.-XLAM1)*(1.+(1./BCOLAM))                              AER03690
     IF(BARLAM-4.0) 2310,2310,2220                                       AER03700
2310 IF(BAR-2.0) 2320,2240,2240                                          AER03710
2320 XBMID1=ALOG(1.65-0.65*XLAM1)                                        AER03720
     GO TO 2235                                                          AER03730
2400 D=D1                                                                AER03740
     ARAT=BAR/BETA1                                                      AER03750
     IF(ARAT-4.0) 20,20,21                                               AER03760
  21 ARAT=4.0                                                            AER03770
  20 ODC=2.*(1.+XLAM1)**1.6*EXP(-.4*ARAT)                                AER03780
     IF(ARAT-1.0) 22,23,23                                               AER03790
  23 IF(XLAM1.LE.0.25) GO TO 27                                          AER03800
     IF(XLAM1.LE.0.75) GO TO 28                                          AER03810
     ODC=ODC-.25*(ARAT-1.)                                               AER03820
     IF(ARAT.LT.2.0) GO TO 22                                            AER03830
     ODC=(2.*(1.+XLAM1)**1.6)*.45-(.85*(ARAT-2.))                        AER03840
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      GO TO 22
   27 ODC=(2.*(1.+XLAM1)**1.6)*.67-(.3*(ARAT-1.0))
      GO TO 22
   28 ODC=(2.*(1.+XLAM1)**1.6)*.67-(.725*(ARAT-1.))
   22 CONTINUE
      RETURN
      END
C
C
      DIMENSION XVXM(16),XDT(16),XAL(48)
      COMMON REFT,SSUBS,XLOB,ZF,VXM,IZZY,LLKK,LLLL,NSURF
      COMMON ICSC, INOSE,ISWPW,IAFBW,ISWPW2,IAFBW2,ISWPT,IAFBT,IDUM1,
     1CLAMT,CLAMW,CLAMW2,D,XLNOSE,BT,BW,BW2,CROOTW,CTOOTT,CTOOW2,
     2ST,SW,SW2,TOVCW,TOVCW2,TOVCT,XLAMT,XLAMW,XLAMW2,
     3XMACW,XMACW2,XMACT,XWING,XWING2,XTAIL,HT,XL,AREA,XREF,
     4ISWEPW,ISWEPT,ISWEP2,NWING,NTAIL,NWING2,ENGINE,ENLET,BETA,DBASE,
     5DJET,XLABOD
      COMMON ART,ARW,ARW2,BAR,BCOLAM,BETA1,B1,CLALT,CLALW,CLALW2,CLAL1,
     1COLAM,CROOT,IAFB,ISWP,TOVC,ODC,XBCRBW,XBCRWB,XKBT,XKBW,XKTB,XKTBT,
     2XKWB,XKWBI,ISWP1,RATIO,XLAM1,XMAC,D1
      IL = 0
      IABC=0
      ISWPW2=0
      IAFBW2=0
      XLAMW2=.0
      CLAMW2=.0
      BW2=.0
      CROOW2=.0
      SW2=.0
      XMACW2=.0
      XWING2=.0
      ISWEP2=0
      NWING2=0
 3040 FORMAT(2I5, 7F10.5)
 3050 FORMAT(6I5)
 3020 FORMAT(7F10.3)
 3010 FORMAT(15A4)
 3110 FORMAT(1H1,15A4)
 3120 FORMAT(6X,2HHT,9X,2HD  ,8X,2HXL,6X,6HXLNOSE,5X,3HXCG,6X,4HAREA,6X,
     14HXREF)
 3021 FORMAT( //,5X,5HTOVCW,5X,6HTOVCW2,5X,5HTOVCT,5X,'ISWEPW',5X,'ISWEPT
     1',5X,'ISWEP2',5X,'NWING',5X,'NTAIL',5X,'NWING2')
 3140 FORMAT ( 3X, I5,  5X, I5,  4X, 7F15.6,//)
 3150 FORMAT(4X,I5,5X,I5,5X,I5,5X,I5,6X,I5,5X,I5)
 3240 FORMAT ( 6X,5HISWPW,  5X,5HIAFBW, 10X, 5HXLAMW, 10X, 5HCLAMW,
     1  10X,5H BW  ,9X,6HCROOTW,10X,5H SW  ,10X,5HXMACW,10X,5HXWING,/)
 3244  FORMAT ( 6X,6HISWPW2, 4X,6HIAFBW2, 9X, 6HXLAMW2, 9X, 6HCLAMW2,
     1 10X,5H BW2 ,9X,6HCROOW2,10X,5H SW2 ,9X,6HXMACW2,9X,6HXWING2,/)
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3248 FORMAT ( 6X,5HISWPT,  5X,5HIAFBT, 10X, 5HXLAMT, 10X, 5HCLAMT,      AER04330
    1 10X,5H BT  ,9X,6HCROOTT,10X,5H ST  ,10X,5HXMACT,10X,5HXTAIL,/)   AER04340
3241 FORMAT(//,6X,5HICSC ,5X,5HINOSE,5X,5HNDELT,5X,5HNMACH,5X,5HNALPH,  AER04350
    15X,5HNBODY)                                                         AER04360
 333 FORMAT(3F10.3,6I2)                                                  AER04370
 334 FORMAT(1X,3F10.3,5X,I4,7X,I4,7X,I4,7X,I4,7X,I4,7X,I4)               AER04380
3335 FORMAT(//,5X,'ENGINE',5X,'ENLET',5X,'BETA',5X,'DBASE',5X,'DJET',    AER04390
    15X,'XLOBOD',5X,'CDPROT')                                            AER04400
3333 WRITE(6,30010)                                                      AER04410
30010 FORMAT(/,1X,'INPUT TITLE')                                         AER04420
     READ 3010, TITL1,TITL2,TITL3,TITL4,TITL5,TITL6,TITL7,TITL8,TITL9,   AER04430
    1TITL0,TITL01,TITL02,TITL03,TITL04,TITL05                            AER04440
1112 FORMAT (I2)                                                         AER04450
1115 FORMAT (F10.3)                                                      AER04460
60001 WRITE(6,10010)                                                     AER04470
10010 FORMAT(/,1X,'INPUT CONTROL CONSTANT, 1=TAIL CONTROL,2=WING CONTROLAER04480
    1,3=CANARD CONTROL')                                                 AER04490
     READ 1112,ICSC                                                      AER04500
     IF(IABC.EQ.1)GO TO 55000                                            AER04510
60002 WRITE(6,10020)                                                     AER04520
10020 FORMAT(/,1X,'INPUT NOSE SHAPE, 1=ELLIPSOID,2=OGIVE,                AER04530
    13=CONE')                                                            AER04540
     READ 1112,INOSE                                                     AER04550
     IF(IABC.EQ.1)GO TO 55000                                            AER04560
60003 WRITE(6,10030)                                                     AER04570
10030 FORMAT(/,1X,'INPUT NUMBER OF CONTROL DEFLECTIONS')                 AER04580
     READ 1112,IDT                                                       AER04590
     IF(IABC.EQ.1)GO TO 55000                                            AER04600
60004 WRITE(6,10040)                                                     AER04610
10040 FORMAT(/,1X,'INPUT NUMBER OF MACH NUMBERS')                        AER04620
     READ 1112,IM                                                        AER04630
     IF(IABC.EQ.1)GO TO 55000                                            AER04640
60005 WRITE(6,10050)                                                     AER04650
10050 FORMAT(/,1X,'INPUT NUMBER OF ANGLES OF ATTACK')                    AER04660
     READ 1112,IAL                                                       AER04670
     IF(IABC.EQ.1)GO TO 55000                                            AER04680
60006 WRITE(6,10060)                                                     AER04690
10060 FORMAT(/,1X,'INPUT NUMBER OF CONFIGURATIONS')                      AER04700
     READ 1112,NBODY                                                     AER04710
     IF(IABC.EQ.1)GO TO 55000                                            AER04720
60007 WRITE(6,10070)                                                     AER04730
10070 FORMAT(/,1X,'INPUT, 1=NON-DELTA WING, 2=DELTA WING')               AER04740
     READ 1112, ISWPW                                                    AER04750
     IF(IABC.EQ.1)GO TO 55000                                            AER04760
60008 WRITE(6,10080)                                                     AER04770
10080 FORMAT(/,1X,'0=NO BODY AFTER WING, 1=BODY AFTER WING')             AER04780
     READ 1112, IAFBW                                                    AER04790
     IF(IABC.EQ.1)GO TO 55000                                            AER04800
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60009 WRITE(6,10090)                                                AER04810
10090 FORMAT(/,1X,'INPUT WING SWEEP CONSTANT')                      AER04820
      WRITE(6,55001)                                                AER04830
55001 FORMAT(1X,'IF DELTA PLANFORM ENTER 0, OTHERWISE')             AER04840
      WRITE(6,1113)                                                 AER04850
 1113 FORMAT(1X,'0=UNSWEPT LEADING EDGE')                           AER04860
      WRITE(6,1114)                                                 AER04870
 1114 FORMAT(1X,'1=SWEPT LEADING EDGE')                             AER04880
      READ 1112,ISWEPW                                              AER04890
      IF(IABC.EQ.1)GO TO 55000                                      AER04900
60010 WRITE(6,10100)                                                AER04910
10100 FORMAT(/,1X,'INPUT NUMBER OF WINGS')                          AER04920
      READ 1112,NWING                                               AER04930
      IF(IABC.EQ.1)GO TO 55000                                      AER04940
60011 WRITE (6,10110)                                               AER04950
10110 FORMAT(/,1X,'INPUT, 1=NON-DELTA TAIL, 2=DELTA TAIL')          AER04960
      READ 1112, ISWPT                                              AER04970
      IF(IABC.EQ.1)GO TO 55000                                      AER04980
60012 WRITE(6,10120)                                                AER04990
10120 FORMAT(/,1X,'0=NO BODY AFTER TAIL, 1=BODY AFTER TAIL')        AER05000
      READ 1112,IAFBT                                               AER05010
      IF(IABC.EQ.1)GO TO 55000                                      AER05020
60013 WRITE(6,10130)                                                AER05030
10130 FORMAT(/,1X,'INPUT TAIL SWEEP CONSTANT')                      AER05040
      WRITE(6,55001)                                                AER05050
      WRITE(6,1113)                                                 AER05060
      WRITE(6,1114)                                                 AER05070
      READ 1112, ISWEPT                                             AER05080
      IF(IABC.EQ.1)GO TO 55000                                      AER05090
60014 WRITE(6,10140)                                                AER05100
10140 FORMAT(/,1X,'INPUT NUMBER OF TAILS')                          AER05110
      READ 1112, NTAIL                                              AER05120
      IF(IABC.EQ.1)GO TO 55000                                      AER05130
60015 WRITE(6,10150)                                                AER05140
10150 FORMAT(/,1X,'INPUT TIP-TO-CHORD RATIO OF WING')               AER05150
      READ 1115,XLAMW                                               AER05160
      IF(IABC.EQ.1)GO TO 55000                                      AER05170
60016 WRITE(6,10160)                                                AER05180
10160 FORMAT(/,1X,'INPUT LEADING EDGE SWEEP OF WING,(DEGS)')        AER05190
      READ 1115, CLAMW                                              AER05200
      IF(IABC.EQ.1)GO TO 55000                                      AER05210
60017 WRITE(6,10170)                                                AER05220
10170 FORMAT(/,1X,'INPUT WING SPAN, INCLUDE BODY')                  AER05230
      READ 1115, BW                                                 AER05240
      IF(IABC.EQ.1)GO TO 55000                                      AER05250
60018 WRITE (6,10180)                                               AER05260
10180 FORMAT(/,1X,'INPUT WING ROOT CHORD(AT BODY JUNCTION)')        AER05270
      READ 1115, CROOTW                                             AER05280
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      IF(IABC.EQ.1)GO TO 55000
60019 WRITE(6,10190)
10190 FORMAT(/,1X,'INPUT EXPOSED WING AREA (2 PANELS)')
      READ 1115,SW
      IF(IABC.EQ.1)GO TO 55000
60020 WRITE(6,10200)
10200 FORMAT(/,1X,'INPUT WING MEAN GEOMETRIC CHORD')
      READ 1115, XMACW
      IF(IABC.EQ.1)GO TO 55000
60021 WRITE(6,10210)
10210 FORMAT(/,1X,'INPUT DISTANCE FROM NOSE TO WING LE')
      READ 1115, XWING
      IF(IABC.EQ.1)GO TO 55000
60022 WRITE(6,10220)
10220 FORMAT(/,1X,'INPUT WING T/C')
      READ 1115, TOVCW
      IF(IABC.EQ.1)GO TO 55000
60023 WRITE(6,10230)
10230 FORMAT(/,1X,'INPUT TIP-TO-ROOT CHORD RATIO OF TAIL')
      READ 1115, XLAMT
      IF(IABC.EQ.1)GO TO 55000
60024 WRITE(6,10240)
10240 FORMAT(/,1X,'INPUT TAIL LEADING EDGE SWEEP(DEGS)')
      READ 1115, CLAMT
      IF(IABC.EQ.1)GO TO 55000
60025 WRITE(6,10250)
10250 FORMAT(/,1X,'INPUT TAIL SPAN, INCLUDING BODY')
      READ 1115,BT
      IF(IABC.EQ.1)GO TO 55000
60026 WRITE(6,10260)
10260 FORMAT(/,1X,'INPUT TAIL ROOT CHORD')
      READ 1115, CROOTT
      IF(IABC.EQ.1)GO TO 55000
60027 WRITE(6,10270)
10270 FORMAT(/,1X,'INPUT EXPOSED TAIL AREA(2 PANELS)')
      READ 1115,ST
      IF(IABC.EQ.1)GO TO 55000
60028 WRITE(6,10280)
10280 FORMAT(/,1X,'INPUT TAIL MEAN GEOMETRIC CHORD')
      READ 1115, XMACT
      IF(IABC.EQ.1)GO TO 55000
60029 WRITE(6,10290)
10290 FORMAT(/,1X,'INPUT DISTANCE FROM NOSE TO TAIL LE')
      READ 1115,XTAIL
      IF(IABC.EQ.1)GO TO 55000
60030 WRITE(6,10300)
10300 FORMAT(/,1X,'INPUT TAIL T/C')
      READ 1115, TOVCT
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      IF(IABC.EQ.1)GO TO 55000
60031 WRITE(6,10310)
10310 FORMAT(/,1X,'INPUT ALTITUDE')
      READ 1115, HT
      IF(IABC.EQ.1)GO TO 55000
60032 WRITE(6,10320)
10320 FORMAT(/,1X,'INPUT BODY DIAMETER')
      READ 1115, D
      IF(IABC.EQ.1)GO TO 55000
60033 WRITE(6,10330)
10330 FORMAT(/,1X,'INPUT MISSILE LENGTH')
      READ 1115,XL
      IF(IABC.EQ.1)GO TO 55000
60034 WRITE(6,10340)
10340 FORMAT(/,1X,'INPUT NOSE LENGTH')
      READ 1115,XLNOSE
      IF(IABC.EQ.1)GO TO 55000
60035 WRITE(6,10350)
10350 FORMAT(/,1X,'INPUT CG LOCATION(FROM NOSE)')
      READ 1115, XCG
      IF(IABC.EQ.1)GO TO 55000
60036 WRITE(6,10360)
10360 FORMAT(/,1X,'INPUT REFERENCE AREA')
      READ 1115, AREA
      IF(IABC.EQ.1)GO TO 55000
60037 WRITE(6,10370)
10370 FORMAT(/,1X,'INPUT REFERENCE LENGTH')
      READ 1115, XREF
      IF(IABC.EQ.1)GO TO 55000
60038 WRITE(6,10380)
10380 FORMAT(/,1X,'ENGINE CODE, 0.0=TURBOFAN, 1.0=ROCKET')
      READ 1115, ENGINE
      IF(IABC.EQ.1)GO TO 55000
60039 WRITE(6,10390)
10390 FORMAT(/,1X,'INLET CODE, 0.0=FLUSH, 1.0=EXTENDED')
      READ 1115, ENLET
      IF(IABC.EQ.1)GO TO 55000
60040 WRITE(6,10400)
10400 FORMAT(/,1X,'INPUT BOATTAIL ANGLE (DEGS)')
      READ 1115, BETA
      IF(IABC.EQ.1)GO TO 55000
60041 WRITE(6,10410)
10410 FORMAT(/,1X,'INPUT BASE DIAMETER')
      READ 1115, DBASE
      IF(IABC.EQ.1)GO TO 55000
60042 WRITE(6,10420)
10420 FORMAT(/,1X,'INPUT NOZZLE EXIT DIAMETER')
      READ 1115,DJET
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      IF(IABC.EQ.1)GO TO 55000
60043 WRITE(6,10430)
10430 FORMAT(/,1X,'INPUT BOATTAIL LENGTH')
      READ 1115, XLABOD
      IF(IABC.EQ.1)GO TO 55000
60044 WRITE(6,10440)
10440 FORMAT(/,1X,'INPUT PROTUBERANCE DRAG')
      READ 1115,CDPROT
      IF(IABC.EQ.1)GO TO 55000
      PRINT 3110, TITL1,TITL2,TITL3,TITL4,TITL5,TITL6,TITL7,TITL8,TITL9,
     1TITLO,TITL01,TITL02,TITL03,TITL04,TITL05
      PRINT 3241
      PRINT 3150, ICSC,INOSE,IDT,IM,IAL,NBODY
      PRINT 3240
      PRINT 3140, ISWPW,IAFBW,XLAMW,CLAMW,BW,CROOTW,SW,XMACW,XWING
      PRINT 3244
      PRINT 3140, ISWPW2,IAFBW2,XLAMW2,CLAMW2,BW2,CROOW2,SW2,XMACW2,
     1XWING2
      PRINT 3248
      PRINT 3140, ISWPT,IAFBT,XLAMT,CLAMT,BT,CROOTT,ST,XMACT,XTAIL
      PRINT 3120
      PRINT 3020, HT,D,XL,XLNOSE,XCG,AREA,XREF
      PRINT 3021
      PRINT 334, TOVCW,TOVCW2,TOVCT,ISWEPW,ISWEPT,ISWEP2,NWING,NTAIL,
     1NWING2
      PRINT 3335
      PRINT 3020, ENGINE,ENLET,BETA,DBASE,DJET,XLABOD,CDPROT
      IABC=1
55000 WRITE(6,59990)
59990 FORMAT(/,1X,'IS INPUT DATA CORRECT?, 0=YES, 1=NO')
      READ 1112, IANS
      IF(IANS.EQ.0)GO TO 70000
      WRITE(6,60000)
60000 FORMAT(/,1X,'ENTER NUMBER OF VARIABLE TO BE CHANGED')
      READ 1112,IVAR
      GO TO (60001,60002,60003,60004,60005,60006,60007,60008,60009,
     160010,60011,60012,60013,60014,60015,60016,60017,60018,60019,
     260020,60021,60022,60023,60024,60025,60026,60027,60028,60029,
     360030,60031,60032,60033,60034,60035,60036,60037,60038,60039,
     460040,60041,60042,60043,60044),IVAR
70000 CONTINUE
      PIE=3.14159
       IL = 1 + IL
      LLKK=0
      LLLL=0
       XCG2 = XCG
       IZZY = 0
      IF(INOSE.EQ.3)GO TO 9961
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      IF(INOSE.EQ.2)GO TO 9959
      XC=XL/2.
      AP=XL*D
      GO TO 9965
 9959 XLNOD=XLNOSE/D
      RADIUS=XLNOD**2+.25
      APOD2=XLNOD*SQRT(RADIUS**2-XLNOD**2)+RADIUS**2
     1*ARSIN(XLNOD/RADIUS)-2.*XLNOD*(RADIUS-.5)
      APN=APOD2*D*D
      AP=(XL-XLNOSE)*D+APN
      XCOD1=RADIUS**3-(RADIUS**2-XLNOD**2)**1.5
      XCOD=XLNOD-(.6667*XCOD1-XLNOD**2*(RADIUS-.5))/APOD2
      XCMOVE=XCOD*D-XLNOSE/2.
      XC=XL/2.+XCMOVE
      GO TO 9965
 9961 APN=.5*D*XLNOSE
      AP=APN+(XL-XLNOSE)*D
      XCN=.6667*XLNOSE
      XCMOVE=XCN-XLNOSE/2.
      XC=XL/2.+XCMOVE
 9965 CONTINUE
      CALL GEOSUB
      DO 10000 I=1,IDT
      WRITE(6,10450)
10450 FORMAT(/,1X,'INPUT CONTROL DEFLECTION')
10000 READ 1115, XDT(I)
      DO 20000 I=1,IM
      WRITE(6,10460)
10460 FORMAT(/,1X,'INPUT MACH NUMBER')
20000 READ 1115, XVXM(I)
      DO 30000 I=1,IAL
      WRITE(6,10470)
10470 FORMAT(/,1X,'INPUT ANGLE OF ATTACK')
30000 READ 1115, XAL(I)
      VXM=XVXM(1)
      RE=REFT*VXM
      DO 6002 IJ=1,IM
      DELTA1=XDT(1)
      DO 6001 II=1,IDT
      ALPHA=XAL(1)
 4000 FORMAT(16F5.1)
 5000 FORMAT(1H1,4HVXM=,F5.2,2X,6HDELTA=,F6.2,/)
 5001 FORMAT(2X,'AL',1X,'CLTOT',1X,'CDTOT',2X,'CLWP',2X,'CLBW',2X,'CLTP'
     1,2X,'CLBT',3X,'CLB',2X,'CDI',3X,'CNWP',3X,'CNTP',2X,'CLTD',2X,'CDT
     2D',2X,'CN',3X,'CA',3X,'XCPW',3X,'XCPT',2X,'XCPB',2X,'XCP',4X,'CM',
     3/)
 8200 PRINT 5000, VXM,DELTA1
      PRINT 5001
```

```
      DELTA=DELTA1/57.29578+.000000001                                  AER07210
      DO 6000 J=1,IAL                                                   AER07220
      AL=ALPHA/57.29578+.00000001                                       AER07230
      SINAAL=SIN(AL)                                                    AER07240
      COSAAL=COS(AL)                                                    AER07250
    1 VXMR1=VXM                                                         AER07260
      IZZY=IZZY+1                                                       AER07270
       IF (IZZY -4) 6666,6666,1111                                      AER07280
 6666 VXM=.6                                                            AER07290
 1111 CALL CLASUB                                                       AER07300
      IF(LLLL-1) 900,942,980                                            AER07310
  900 IF(IZZY-4) 6009,6009,925                                          AER07320
  925 CALL CATSUB                                                       AER07330
 6009 XLAM14=ATAN((.5*(B1-D)*1./COLAM+.25*XLAM1*CROOT-.25*CROOT)/       AER07340
     1(.5*(B1-D)))                                                      AER07350
      RE=REFT*VXM*XMAC                                                  AER07360
      IF (RE-1.E06) 6010,6020,6020                                      AER07370
 6010 AA=.0835                                                          AER07380
      XNN=-.211                                                         AER07390
       GO TO 6070                                                       AER07400
 6020 IF (RE-1.E07) 6030,6040,6040                                      AER07410
 6030 AA=.052                                                           AER07420
      XNN=-.177                                                         AER07430
       GO TO 6070                                                       AER07440
 6040 IF (RE-1.E08) 6050,6060,6060                                      AER07450
 6050 AA=.0333                                                          AER07460
      XNN=-.1488                                                        AER07470
      GO TO 6070                                                        AER07480
 6060 AA=.0221                                                          AER07490
      XNN=-.127                                                         AER07500
 6070 CF=AA*RE**XNN                                                     AER07510
      SURF=FLOAT(NSURF)                                                 AER07520
      CDO=SURF*CF*(1.+2.*TOVC+100.*TOVC**4.)                            AER07530
      IF (IZZY-4) 6091,6091,6092                                        AER07540
 6091 IF (IZZY-3) 6093,6094,6095                                        AER07550
 6092 IF (AL)  2401,2402,2402                                           AER07560
 2401 ODC=-ODC                                                          AER07570
 2402 LLKK=LLKK+1                                                       AER07580
      IF (LLKK-2) 2403,2404,2420                                        AER07590
 2403 IF (SW) 2410,2410,2420                                            AER07600
 2410 LLKK=LLKK+1                                                       AER07610
 2404 IF (SW2) 2411,2411,2420                                           AER07620
 2411 LLKK=LLKK+1                                                       AER07630
 2420 IF (LLKK-2) 930,943,950                                           AER07640
  930 XKWBW=XKWB                                                        AER07650
      XKBWW=XKBW                                                        AER07660
      IF(ISWEPW.EQ.0) GO TO 963                                         AER07670
      SHIFT=TAN(CLAMW)*(BW-D)/4.0                                       AER07680
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```
      GO TO 965
  963 SHIFT=0.0
  965 XCPWB=XWING+XBCRWB*CROOT+SHIFT
      XCPBW=XWING+XBCRBW*CROOT
      ODCW=ODC
      CLW=SIN(AL)*(XKWBW+XKBWW)*CLALW*SW*COS(AL)/AREA
      CLWB=SIN(AL)*XKWBW*CLALW*SW*COS(AL)/AREA
      CLBW=CLW-CLWB
      CLVISW=    (SIN(AL)*SIN(AL)*SW*COS(AL)/AREA)*ODCW
      CLW=CLW+CLVISW
      CLWP=CLWB+CLVISW
 6093 CDOW=CDO*(SW)/AREA
      XLAMW4=XLAM14
      TOVCW=TOVC
      SWTOT=SW
      IZZY=IZZY+1
      IF(SW2) 942,942,511
  511 COLAM=COS(CLAMW2)/SIN(CLAMW2)
      CDOW2=0.
      BCOLAM=BETA1*COLAM
      CROOT=CROOW2
      B1=BW2
      IAFB=IAFBW2
      CLAL1=CLALW2
      XLAM1=XLAMW2
      TOVC=TOVCW2
      XMAC=XMACW2
      ISWP1=ISWPW2
      BAR=BETA1*ARW2
      RATIO=CROOT/(BETA1*D)
      IF(IZZY-4) 6009,6009,925
  943 XKWBW2=XKWB
      XKBWW2=XKBW
      IF(ISWEP2.EQ.0) GO TO 948
      SHIFT=TAN(CLAMW2)*(BW2-D)/4.0
      GO TO 949
  948 SHIFT=0.
  949 XCPWB2=XWING2+XBCRWB*CROOT+ SHIFT
      XCPBW2=XWING2+XBCRBW*CROOT
      ODCW2=ODC
      CLW2=SIN(AL)*(XKWBW2+XKBWW2)*CLALW2*SW2*COS(AL)/AREA
      CLWB2=SIN(AL)*XKWBW2*CLALW2*SW2*COS(AL)/AREA
      CLBW2=CLW2-CLWB2
      CLVIW2=(SIN(AL)*SIN(AL)*SW2*COS(AL)/AREA)*ODCW2
      CLW2=CLW2+CLVIW2
 6094 CDOW2=CDO*(SW2)/AREA
      XLAM24=XLAM14
      SW2TOT=SW2
```

```
  942  IZZY = IZZY +1                                                  AER08170
       LLKK=LLKK+2                                                     AER08180
        IF (ST) 980,980,940                                            AER08190
  940  COLAM=COS(CLAMT)/SIN(CLAMT)                                     AER08200
       ART=(BT-D)**2/ST                                                AER08210
       BCOLAM=BETA1*COLAM                                              AER08220
       CROOT=CROOTT                                                    AER08230
       B1=BT                                                           AER08240
       BAR=BETA1*ART                                                   AER08250
       CLAL1=CLALT                                                     AER08260
       IAFB=IAFBT                                                      AER08270
       XMAC=XMACT                                                      AER08280
       TOVC=TOVCT                                                      AER08290
       ISWP1=ISWPT                                                     AER08300
       XLAM1=XLAMT                                                     AER08310
       RATIO=CROOT/(BETA1*D)                                           AER08320
        IF (IZZY-4) 6009,6009,925                                      AER08330
  950  XKWBT=XKWB                                                      AER08340
       XKBWT=XKBW                                                      AER08350
       XCPBT=XTAIL+XBCRBW*CROOT                                        AER08360
       ODCT=ODC                                                        AER08370
       CLT=((XKWBT+XKBWT)*SIN(AL))*CLALT*ST*COS(AL)/AREA               AER08380
       CLTB=SIN(AL)*XKWBT*CLALT*ST*COS(AL)/AREA                        AER08390
       CLBT=CLT-CLTB                                                   AER08400
       CLTD=XKTB*CLALT*SIN(DELTA)*ST*COS(AL+DELTA)/AREA                AER08410
       CLTDB=(XKTB+XKBT)*CLALT*SIN(DELTA)*ST*COS(AL+DELTA)/AREA        AER08420
       CLBDT=CLTDB-CLTD                                                AER08430
       CLBT=CLBT+CLBDT                                                 AER08440
       CLVIST=((SIN(AL+DELTA)*SIN(AL+DELTA))*ST*COS(AL+DELTA)/AREA)*ODCT AER08450
       CLT=CLT+CLVIST                                                  AER08460
       CLTP=CLTB+CLVIST+CLTD                                           AER08470
 6095  CDOT=CDO*(ST)/AREA                                              AER08480
       STTOT=ST                                                        AER08490
       XLAMT4=XLAM14                                                   AER08500
        IF (IZZY-4) 1610,1610,6098                                     AER08510
 6098  IF(ISWEPT.EQ.0) GO TO 6097                                      AER08520
       SHIFT=TAN(CLAMT)*(BT-D)/4.0                                     AER08530
       GO TO 6099                                                      AER08540
 6097  SHIFT=0.0                                                       AER08550
 6099  XCPTB=XTAIL+((XKWBT*SIN(AL)*XBCRWB+XKTB*SIN(DELTA)*XBCRWB)/     AER08560
      1(XKWBT*SIN(AL)+XKTB*SIN(DELTA)))*CROOTT+SHIFT                   AER08570
                                                                       AER08580
  980   IF (IZZY - 4) 1610, 1610, 1710                                 AER08590
 1710   XLOB = XL/D                                                    AER08600
       ZXM=VXM*ABS(SIN(AL))                                            AER08610
        IF (ZXM-.8) 1310,1350,1350                                     AER08620
 1310  CDC=2.4-SQRT(1.5129-1.5129*ZXM*ZXM)                             AER08630
       GO TO 1391                                                      AER08640
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1350 IF (ZXM-1.15) 1380,1370,1370                                       AER08650
1380 CDC=1.6+SQRT(.344-(ZXM-.975)**2)                                   AER08660
     GO TO 1391                                                         AER08670
1370 IF (ZXM-3.) 1360,1381,1381                                         AER08680
1360 CDC=1.9-SQRT(.361-.09*(ZXM-3.)**2)                                 AER08690
     GO TO 1391                                                         AER08700
1381 CDC=1.3                                                            AER08710
                                                                        AER08720
1391 ETA=(0.0000475*(XLOB**3))-(0.00173*(XLOB**2))+(0.0298*XLOB)+0.5146AER08730
     IF (VXM-.5) 1395,1395,1392                                         AER08740
1392 IF (VXM-1.4) 1393,1394,1394                                        AER08750
1393 ETA=ETA+(1.-ETA)*(VXM-.5)*1.111                                    AER08760
     GO TO 1395                                                         AER08770
1394 ETA=1.                                                             AER08780
1395 IF (XLOB-10.) 1320,1330,1340                                       AER08790
1320 XK2K1=-0.0054*(XLOB**2)+0.104*XLOB+0.437                           AER08800
     GO TO 1600                                                         AER08810
1330 XK2K1=0.939                                                        AER08820
     GO TO 1600                                                         AER08830
1340 XK2K1=0.939+(0.001525*(XLOB-10.0))                                 AER08840
1600 ALP=AL                                                             AER08850
     IF(AL) 1602,1601,1601                                              AER08860
1602 CDC=-CDC                                                           AER08870
1601 CNB=(XK2K1*SIN(2.*ALP)*COS(ALP/2.))*3.14159*D*D/(4.*AREA)          AER08880
    1+ETA*CDC*((AP   )/AREA)*((SIN(ALP))**2)                            AER08890
     XQ=XCG/D                                                           AER08900
     CMB1=(XK2K1*XQ*SIN(2.*ALP)*COS(ALP/2.))*3.14159*D*D*D/             AER08910
    1(4.*AREA*XREF)                                                     AER08920
     CMB2=(ETA*CDC*((AP   )/AREA)*((XCG-(XC   ))/D)*((SIN(ALP)**2)))    AER08930
    1*D/XREF                                                            AER08940
     CMB=CMB1+CMB2                                                      AER08950
1610 RE=REFT*VXM*XL                                                     AER08960
     IF (RE-1.E06) 1611,1612,1612                                       AER08970
1611 AA=.0835                                                           AER08980
     XNN=-.211                                                          AER08990
     GO TO 1617                                                         AER09000
1612 IF (RE-1.E07) 1613,1614,1614                                       AER09010
1613 AA=.052                                                            AER09020
     XNN=-.177                                                          AER09030
     GO TO 1617                                                         AER09040
1614 IF (RE-1.E08) 1615,1616,1616                                       AER09050
1615 AA=.033                                                            AER09060
     XNN=-.1488                                                         AER09070
     GO TO 1617                                                         AER09080
1616 AA=.0221                                                           AER09090
     XNN=-.127                                                          AER09100
1617 CFBOD=AA*RE**XNN                                                   AER09110
     CDOB=(1.02*CFBOD*(1.0+.0025*XLOB+60.0/(XLOB**3.0))*SSUBS/AREA)+    AER09120
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 1CDPROT
      IF(ENGINE.EQ.1.0) GO TO 617
      IF(ENLET.EQ.1.0) GO TO 619
      CDINL=.038*CDOB
      GO TO 620
  619 CDINL=0.05*CDOB
      GO TO 620
  617 CDINL=.0
C   ABTERBODY DRAG CALCULATIONS
  620 DELCPO=0.
      DELCPD=0.
      DRATIO=(DBASE**2-DJET**2)/(D**2)
      DRATO1=(DJET**2)/(DBASE*D)
      DBDM=DBASE/D
      DELBAS=-.1532+(.0247*BETA1)-(.002632*(BETA1**2))
      CPBSO1=-.11905+(.00017*DBDM)-(.0283*(DBDM**2))
      CPBSO2=-.0273+(.00425*DBDM)-(.1143*(DBDM**2))
      CPBSO3=-.0612+(.3485*DBDM)-(.4254*(DBDM**2))
      CPBSO4=.0789+(.5252*DBDM)-(.7434*(DBDM**2))
      CPBSO5=-.085+(1.324*DBDM)-(1.407*(DBDM**2))
      IF(BETA-3.0)770,770,772
  770 CPBSO=((CPBSO1+0.15)*BETA/3.0)-.15
      GO TO 800
  772 IF(BETA-5.6)773,773,775
  773 CPBSO=((CPBSO2-CPBSO2)*(BETA-3.0)/2.6)+CPBSO1
      GO TO 800
  775 IF(BETA-8.0)776,776,778
  776 CPBSO=((CPBSO3-CPBSO2)*(BETA-5.6)/2.4)+CPBSO2
      GO TO 800
  778 IF(BETA-16.0)779,779,780
  779 CPBSO=((CPBSO4-CPBSO3)*(BETA-8.0)/8.0)+CPBSO3
      GO TO 800
  780 CPBSO=((CPBSO5-CPBSO4)*(BETA-16.0)/4.0)+CPBSO4
  800 CDBASE=(-DRATIO)*(CPBSO+DELCPO+(DELCPO*DRATO1))
      IF(ENGINE.EQ.1.0)GO TO 618
      IF(DBDM-.76)801,801,802
  801 CBOAT5=.1013*DBDM
      GO TO 810
  802 IF(DBDM.LT.0.82) GO TO 803
      CBOAT5=-.4*(DBDM-.82)+.077
      GO TO 810
  803 CBOAT5=.077
  810 IF(DBDM-.245)811,811,812
  811 CBOAT4=.0653*DBDM
      GO TO 820
  812 IF(DBDM.GT.0.76) GO TO 813
      CBOAT4=.1048*(DBDM-.245)+.016
      GO TO 820
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813 IF(DBDM.GT.0.82) GO TO 814                                          AER09610
    CBOAT4=.071                                                         AER09620
    GO TO 820                                                           AER09630
814 CBOAT4=-.369*(DBDM-.82)+.07                                         AER09640
820 IF(DBDM-.36)821,821,822                                             AER09650
821 CBOAT3=.0292*DBDM                                                   AER09660
    GO TO 830                                                           AER09670
822 IF(DBDM.GT.0.76) GO TO 823                                          AER09680
    CBOAT3=.10125*(DBDM-.36)+.0105                                      AER09690
    GO TO 830                                                           AER09700
823 IF(DBDM.GT.0.81) GO TO 824                                          AER09710
    CBOAT3=.057                                                         AER09720
    GO TO 830                                                           AER09730
824 CBOAT3=-.2579*(DBDM-.81)+.051                                       AER09740
830 IF(DBDM-.32)831,831,832                                             AER09750
831 CBOAT2=.0125*DBDM                                                   AER09760
    GO TO 840                                                           AER09770
832 IF(DBDM.GT.0.5) GO TO 833                                           AER09780
    CBOAT2=.0333*(DBDM-.32)+.004                                        AER09790
    GO TO 840                                                           AER09800
833 IF(DBDM.GT.0.72) GO TO 834                                          AER09810
    CBOAT2=.1068*(DBDM-.5)+.01                                          AER09820
    GO TO 840                                                           AER09830
834 IF(DBDM.GT.0.76) GO TO 835                                          AER09840
    CBOAT2=.0335                                                        AER09850
    GO TO 840                                                           AER09860
835 CBOAT2=-.1354*(DBDM-.76)+.0335                                      AER09870
840 IF(DBDM-.6)841,841,842                                              AER09880
841 CBOAT1=.0055-(.03375*DBDM)+(.06875*(DBDM**2))                       AER09890
    GO TO 850                                                           AER09900
842 IF(DBDM.GT.0.75) GO TO 843                                          AER09910
    CBOAT1=.1*(DBDM-.6)+.01                                             AER09920
    GO TO 850                                                           AER09930
843 IF(DBDM.GT.0.78) GO TO 844                                          AER09940
    CBOAT1=.025                                                         AER09950
    GO TO 850                                                           AER09960
844 CBOAT1=-.091*(DBDM-.78)+.025                                        AER09970
850 IF(BETA-3.0)851,851,852                                             AER09980
851 CBOAT1=(CBOAT1*BETA)/3.0                                            AER09990
    GO TO 875                                                           AER10000
852 IF(BETA-5.6)853,853,854                                             AER10010
853 CBOAT1=((CBOAT2-CBOAT1)*(BETA-3.0)/2.6)+CBOAT1                      AER10020
    GO TO 875                                                           AER10030
854 IF(BETA-8.0)855,855,856                                             AER10040
855 CBOAT1=((CBOAT3-CBOAT2)*(BETA-5.6)/2.4)+CBOAT2                      AER10050
    GO TO 875                                                           AER10060
856 IF(BETA-16.0)857,857,858                                            AER10070
857 CBOAT1=((CBOAT4-CBOAT3)*(BETA-8.0)/8.0)+CBOAT3                      AER10080
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      GO TO 875                                                          AER10090
  858 IF(BETA-24.0)859,859,860                                           AER10100
  859 CBOAT1=((CBOAT5-CBOAT4)*(BETA-16.0)/8.0)+CBOAT4                    AER10110
      GO TO 875                                                          AER10120
  860 PRINT 866                                                          AER10130
  866 FORMAT(1X,'BOATTAIL ANGLE GREATER THAN 24 DEGREES')                AER10140
      CBOAT1=CBOAT5                                                      AER10150
  875 CDBOAT=CBOAT1+DELBAS*(DELCPO+(DELCPD)*(DRATO1))                    AER10160
      CDAFT=CDBOAT+CDBASE                                                AER10170
  618 FR=XLNOSE/D                                                        AER10180
      CDWN1=0.000407*(FR**8.0)-.0102*(FR**7.0)+.108*(FR**6.0)-.616*(     AER10190
     1FR**5.)+2.074*(FR**4.0)-4.183*(FR**3.0)+4.891*(FR**2.0)-3.017*     AER10200
     2FR+.7795                                                           AER10210
      IF(FR.GT.1.0) CDWN1=.7432093E-04*FR**5.0-.15368398E-02*FR**4.0     AER10220
     1+.011741209*FR**3.0-0.039555503*FR**2.0+0.050635882*FR+.005431397  AER10230
      CDPTR=(CDWN1/.8)*VXM                                               AER10240
      CDOB1=CDOB                                                         AER10250
      CDOB=CDOB+CDINL+CDAFT+CDPTR                                        AER10260
      CDOWBT=CDOW+CDOW2+CDOT+CDOB                                        AER10270
      CDMISC=CDOWBT*.1                                                   AER10280
      CDOWBT=CDOWBT+CDMISC                                               AER10290
      IF (IZZY-4) 1618,1618,1619                                         AER10300
 1618 VXM=1.1999999                                                      AER10310
      IF (SW) 1620,1620,1621                                             AER10320
 1620 CDOW=0.                                                            AER10330
 1621 IF (SW2) 1622,1622,1623                                            AER10340
 1622 CDOW2=0.                                                           AER10350
 1623 IF (ST) 1624,1624,1625                                             AER10360
 1624 CDOT=0.                                                            AER10370
 1625 HONST=CDOWBT                                                       AER10380
      GO TO 1639                                                         AER10390
 1619 IF (VXM-1.2) 1639,1639,1632                                        AER10400
 1639  IF (SW) 1700,1700,1701                                            AER10410
 1700  DCDOSW = 0.0                                                      AER10420
       SWTOT=0.0                                                         AER10430
       CDOW = 0.0                                                        AER10440
       GO TO 1702                                                        AER10450
 1701  XXM = VXM*SQRT(COS(XLAMW4))                                       AER10460
      SQMITC=SQRT(ABS((XXM*XXM)-1.0))/(TOVCW**0.33333)                   AER10470
      ATC=ARW*(TOVCW**.333333)                                           AER10480
      IZT=1                                                              AER10490
 1640 IF (ATC-1.5) 1641,1642,1642                                        AER10500
 1642 IF (VXM-1.) 1643,1643,1644                                         AER10510
 1643 FUNCT=3.3081-1.88779*SQMITC+11.0916*SQMITC*SQMITC-18.6087*         AER10520
     1SQMITC**3+7.4633*SQMITC**4                                         AER10530
      FUNCT=FUNCT+(ATC-2.0)*0.1                                          AER10540
      GO TO 1650                                                         AER10550
 1644 FUNCT=3.0+(ATC-1.5)*0.3                                            AER10560
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      GO TO 1650                                                        AER10570
 1641 IF (ATC-.5) 1645,1645,1646                                        AER10580
 1646 IF (VXM-1.) 1647,1647,1648                                        AER10590
 1647 FUNCT=2.47917-1.42798*SQMITC-.324405*SQMITC*SQMITC                AER10600
      IF(SQMITC-0.4)2647,2648,2648                                      AER10610
 2647 FUNCT=FUNCT+(1.8*(ATC-1.0))                                       AER10620
 2648 FUNCT=FUNCT+(0.72*(ATC-1.0))/SQMITC                               AER10630
      GO TO 1650                                                        AER10640
 1648 FUNCT=(0.25*SQMITC)+(ATC*2.3)                                     AER10650
      GO TO 1650                                                        AER10660
 1645 IF (VXM-1.) 1649,1649,1651                                        AER10670
 1649 FUNCT=0.9-(0.7*SQMITC)                                            AER10680
      GO TO 1650                                                        AER10690
 1651 FUNCT=.333*SQMITC+ATC*1.8                                         AER10700
 1650 IF (IZT-2) 1652,1653,1654                                         AER10710
 1652 DCDOSW=FUNCT*(TOVCW**1.66667)*((COS(XLAMW4))**2.5)                AER10720
      IF(SQMITC.GT.1.3)DCDOSW=0.0                                       AER10730
      IF(DCDOSW.LT.0.0)DCDOSW=0.0                                       AER10740
      DCDOW=DCDOSW                                                      AER10750
 1702  IF (SW2) 1703,1703,1704                                          AER10760
 1703  DCDOS2 = 0.0                                                     AER10770
       SW2TOT = 0.0                                                     AER10780
       CDOW2= 0.0                                                       AER10790
       GO TO 1705                                                       AER10800
 1704  IZT = 2                                                          AER10810
      XXM=VXM*SQRT(COS(XLAM24))                                         AER10820
      SQMITC=SQRT(ABS((XXM*XXM)-1.))/(TOVCW2**0.33333)                  AER10830
      ATC=ARW2*(TOVCW2**.33333)                                         AER10840
      GO TO 1640                                                        AER10850
 1653 DCDOS2=FUNCT*(TOVCW2**1.66667)*((COS(XLAM24))**2.5)               AER10860
      IF(SQMITC.GT.1.3)DCDOS2=0.0                                       AER10870
      IF(DCDOS2.LT.0.0)DCDOS2=0.0                                       AER10880
      DCDOW2=DCDOS2                                                     AER10890
 1705  IF (ST ) 1706,1706,1707                                          AER10900
 1706  DCDOST = 0.0                                                     AER10910
      STTOT=0.0                                                         AER10920
       CDOT = 0.0                                                       AER10930
       GO TO 1708                                                       AER10940
 1707  IZT = 3                                                          AER10950
      XXM=VXM*SQRT(COS(XLAMT4))                                         AER10960
      SQMITC=SQRT(ABS((XXM*XXM)-1.0))/(TOVCT**0.33333)                  AER10970
      ATC=ART*(TOVCT**.33333)                                           AER10980
      GO TO 1640                                                        AER10990
 1654 DCDOST=FUNCT*(TOVCT**1.66667)*((COS(XLAMT4))**2.5)                AER11000
      IF(SQMITC.GT.1.3)DCDOST=0.0                                       AER11010
      IF(DCDOST.LT.0.0)DCDOST=0.0                                       AER11020
      DCDOT=DCDOST                                                      AER11030
 1708 IF(VXM-1.0)7707,7707,7706                                         AER11040
```

```
 7706 IF(VXM-2.0) 7705,7708,7708
C   TRANSONIC  BODY  DRAG
 7707 COVC=1.0-(0.08*VXM)
      GO TO 7709
 7705 COVC=0.92-(0.12*(VXM-1.0))
      GO TO 7709
 7708  COVC =  1.31213-0.36633*VXM+.06038*VXM**2-.00601*VXM**3+.000275*
     1VXM**4
 7709 CDFPTR=1.02*CFBOD*COVC*SSUBS/AREA
        CDPPTR=CDOB1-1.02*CFBOD*SSUBS/AREA
      IF(VXM-1.0) 1709,1709,1711
 1711 CDPPTR=(CDPPTR/0.2)*(1.2-VXM)
 1709 IF(FR.GT.2.0) GO TO 750
      CDWN2=0.000172*(FR**8)-0.00453*(FR**7)+0.050*(FR**6)-0.304*(FR**5)
     1+1.096*(FR**4)-2.406*(FR**3)+3.160*(FR**2)-2.391*(FR)+1.00
      CDWN3=.000125*(FR**8)-.00370*(FR**7)+.0447*(FR**6)-.288*(FR**5)
     1+1.076*(FR**4)-2.385*(FR**3)+3.141*(FR**2)-2.529*FR+1.300
      GO TO 760
  750 CDWN2=-.33793095E-03*FR**5.0+.76402056E-02*FR**4.0-.67397615E-01*
     1FR**3.0+.29429971*FR**2.0-.65782772*FR+.65397474
      CDWN3=-.36714382E-03*FR**5.0+.88164977E-02*FR**4.0-.83661489E-01*
     1FR**3.0+.39748005*FR**2.0-.9686696*FR+1.0327385
  760 IF(VXM-.8) 1658,1661,1662
 1661 CDPTR=CDWN1
      GO TO 1658
 1662 IF(VXM-1.0) 1655,1665,1666
 1665 CDPTR=CDWN2
      GO TO 1658
 1655 CDPTR=((CDWN2-CDWN1)/0.2)*(VXM-0.8)+CDWN1
      GO TO 1658
 1666 IF(VXM-1.2) 1667,1668,1664
 1668 CDPTR=CDWN3
      GO TO 1658
 1667 CDPTR=((CDWN3-CDWN2)/0.2)*(VXM-1.0)+CDWN2
      GO TO 1658
 1664 CDPTR=0.0
 1658 CDOB=CDFPTR+CDPPTR+CDINL+CDAFT+CDPTR
      CDALZ=CDOB
      CDOT=1.1*(DCDOST*(STTOT/AREA)+CDOT)
      CDOW=1.1*(DCDOSW*(SWTOT/AREA)+CDOW)
      CDOW2=1.1*(CDOW2+DCDOS2*(SWTOT/AREA))
      CDOWBT=CDOB+CDOT+CDOW+CDOW2+CDMISC
      IF (IZZY-4) 1659,1659,1663
 1659 TONST=CDOWBT
      HONST=HONST+ZF*(TONST-HONST)
      VXM=VXMR1
       IZZY =  IZZY + 1
      GO TO 1
```

```
1632 CDOWBT=((HONST-TONST)/(SQRT(3.)-SQRT(1.2)))*SQRT(VXM)+TONST
    1+(HONST-TONST)/(1.-SQRT(3.)/SQRT(1.2))
     CDOT=1.1*(DCDOT *(STTOT/AREA)+CDOT)
     CDOW=1.1*(DCDOW *(SWTOT/AREA)+CDOW)
     CDOW2=1.1*(CDOW2+DCDOW2*(SWTOT/AREA))
     CDOB=CDOWBT-CDOT-CDOW-CDOW2
     CDALZ=CDOB
1663 CDB=XK2K1*SIN(2.*AL)*SIN(AL/2.)*3.14159*D*D/(4.*AREA)+ETA*
    1CDC*AP*((SIN(AL))**3)/AREA
     CLB=XK2K1*(SIN(2.*AL))*COS(AL/2.)*COS(AL)*3.14159*D*D/(4.*AREA)+ETA
    1A*CDC*AP*((SIN(AL))**2)*COS(AL)/AREA-CDALZ*COS(AL)*COS(AL)*SIN(A
    2L)
     CA5=CDOWBT
     IF(AL) 1603,1604,1603
1604 XCPB=0.0
     GO TO 1605
1603 XCPB=((XCG/XREF)-(CMB/CNB))*XREF
1605 IF (SW) 1607,1607,1606
1606 IF (ST) 2973,2973,1608
1607 IF (ST) 1990,1990,2974
1608 R=D/2.
      IF (ICSC -1) 1970,1970,1971
1971 XB1=BW/2.
     XB2=BT/2.
     TT=D/BT
     HW1=-0.5*CROOTT*ABS(SIN(DELTA))+(XCPWB-XTAIL-CROOTT)*ABS(SIN(AL))
     XLAM1=XLAMW
     GO TO 1969
1970 XB1=BT/2.
     XB2=BW/2.
     TT=D/BW
     HW1=-0.5*CROOTT*ABS(SIN(DELTA))+(XCPWB-XTAIL-CROOTT)*ABS(SIN(AL))
     XLAM1=XLAMT
1969 FTRT=((XB2-R)/(2.*(1.-TT)))*((3.14159/4.)-((3.14159*TT**2)/4.)-TT+
    1(((1.+TT**2)**2)/(2.*(1.-TT**2)))*ARSIN((1.-TT**2)/(1.+TT**2)))
     FW=FTRT+R
     FI1=(FW*R**2)/((FW**2)+(HW1**2))
     HI1=(HW1*R**2)/((FW**2)+(HW1**2))
     ZC=FW
     ZD=HW1
     ZLT=0.0
     DO 1800 I=1,4
     ZL1=((XB1-(XLAM1*R))-(ZC*(1.-XLAM1)))/(2.*(XB1-R))
     ZL2=ALOG(((ZD**2)+((ZC-XB1)**2))/((ZD**2)+((ZC-R)**2)))
     ZL3=((1.-XLAM1)/(XB1-R))*((XB1-R)+(ZD*(ATAN((ZC-XB1)/ZD)-ATAN((ZC-
    1R)/ZD))))
     ZL=(ZL1*ZL2)-ZL3
     IF(I-2) 1810,1820,1820
```

```
1810 ZC=-ZC                                                             AER12010
     GO TO 1850                                                         AER12020
1820 IF(I-3) 1830,1840,1850                                             AER12030
1830 ZL=-ZL                                                             AER12040
     ZC=FI1                                                             AER12050
     ZD=HI1                                                             AER12060
     GO TO 1850                                                         AER12070
1840 ZL=-ZL                                                             AER12080
     ZC=-FI1                                                            AER12090
1850 ZLT=ZLT+ZL                                                         AER12100
1800 CONTINUE                                                           AER12110
     IF(ICSC-1) 2970,2970,2971                                          AER12120
2970 ART=(BT-D)**2/ST                                                   AER12130
     XBT=BT/2.                                                          AER12140
     CLI=(CLALW*CLALT*XKWBI*SIN(AL)*SW*2.*ZLT*(XBT-R))/(2.*3.14159*ART*AER12150
    1FTRT*AREA*(1.+XLAMT))                                              AER12160
     CLI=CLI*COS(AL)                                                    AER12170
     CLTP=CLTP+CLI                                                      AER12180
     CLT=CLT+CLI                                                        AER12190
     CLIT=CLI                                                           AER12200
     CLIW=0.                                                            AER12210
     XCPTV=XCPTB                                                        AER12220
     GO TO 2972                                                         AER12230
2971 ARW=(BW-D)**2/SW                                                   AER12240
     XBW=BW/2.                                                          AER12250
     CLI=(CLALW*CLALT*(XKWBI*SIN(AL)+XKTBI*SIN(DELTA))*ST*2.*ZLT*(XBW-  AER12260
    1R))/(2.*3.14159*ARW*FTRT*AREA*(1.+XLAMW))                          AER12270
     CLI=CLI*COS(AL)                                                    AER12280
     CLW=CLW+CLI                                                        AER12290
     CLWP=CLWP+CLI                                                      AER12300
     CLIW=CLI                                                           AER12310
     CLIT=0.                                                            AER12320
     XCPTV=XCPWB                                                        AER12330
     GO TO 2972                                                         AER12340
2973 CLT=0.                                                             AER12350
     CLALT=0.                                                           AER12360
     CLTD=0.                                                            AER12370
     CDTD=0.                                                            AER12380
     CLBT=0.                                                            AER12390
     CLBDT=0.                                                           AER12400
     CLTB=0.                                                            AER12410
     CLTDB=0.                                                           AER12420
     CLVIST=0.                                                          AER12430
     CLIT=0.                                                            AER12440
     CLIW=0.                                                            AER12450
     CLI=0.                                                             AER12460
     CLTP=0.                                                            AER12470
     GO TO 2972                                                         AER12480
```

```
 2974 CLW=0.                                                            AER12490
      CLALW=0.                                                          AER12500
      CLBW=0.                                                           AER12510
      CLWB=0.                                                           AER12520
      CLVISW=0.                                                         AER12530
      CLIW=0.                                                           AER12540
      CLIT=0.                                                           AER12550
      CLI=0.                                                            AER12560
 2972 IF (SW2) 700,700,701                                              AER12570
  700 CLW2=0.                                                           AER12580
      CLALW2=0.                                                         AER12590
      CLBW2=0.                                                          AER12600
      CLWB2=0.                                                          AER12610
C INDUCED DRAG                                                          AER12620
  701 ALPHA=AL                                                          AER12630
      CLTOT=CLWP+CLTP+CLB+CLBW+CLBT                                     AER12640
      IF(ARW.GT.3.0) GO TO 9975                                         AER12650
      IF(VXM.GE..85) GO TO 9975                                         AER12660
      CDI=ABS(CLTOT*TAN(ALPHA))                                         AER12670
      GO TO 9977                                                        AER12680
 9975 CDI=(CLTOT)**2/(PIE*BW**2*.7/AREA)                                AER12690
 9977 IF(BT)9978,9979,9978                                              AER12700
 9978 AR1=BT**2/AREA                                                    AER12710
      CDTD=CLTD**2/(PIE*AR1*.7)                                         AER12720
      CDT=CDOT+(CLTP**2/(PIE*AR1*.7))                                   AER12730
 9979 IF(BW2)9980,9981,9980                                             AER12740
 9980 AR2=BW2**2/AREA                                                   AER12750
      CDW2=CDOW2+(CLW2**2/(PIE*AR2*.7))                                 AER12760
 9981 IF(BW)9982,9983,9982                                              AER12770
 9982 AR3=BW**2/AREA                                                    AER12780
      CDW=CDOW+(CLWP**2/(PIE*AR3*.7))                                   AER12790
C   AXIAL AND NORMAL COMPONENTS                                         AER12800
 9983 CATD=CDTD*COSAAL-CLTD*SINAAL                                      AER12810
      CNTD=CLTD*COSAAL+CDTD*SINAAL                                      AER12820
      CNT=CLT*COSAAL+CDT*SINAAL                                         AER12830
      CNTP=(CLTP+CLTD)*COSAAL+(CDT+CDTD)*(SINAAL)                       AER12840
      CNW=CLW*COSAAL+CDW*SINAAL                                         AER12850
      CNWP=CLWP*COSAAL+CDW*SINAAL                                       AER12860
      CNW2=CLW2*COSAAL+CDW2*SINAAL                                      AER12870
      CAB=(CDOB+CDB)*COSAAL-CLB*SINAAL                                  AER12880
      CAW=CDW*COSAAL-CLW*SINAAL                                         AER12890
      CAW2=CDW2*COSAAL-CLW2*SINAAL                                      AER12900
      CAT=CDT*COSAAL-CLT*SINAAL                                         AER12910
      CA5=CAT+CAW+CAW2+CATD+CAB                                         AER12920
      GO TO 1991                                                        AER12930
 1990 CN=CNB                                                            AER12940
      XCP2=XCPB                                                         AER12950
      IF(XAL(J).GT.90.)GO TO 9993                                       AER12960
```

```
      CA=CA5*COS(AL)*COS(AL)                                            AER12970
      GO TO 9994                                                        AER12980
 9993 CA51=-(.5667+.893*VXM-.1727*VXM*VXM)                              AER12990
      CA=CA51*COS(AL)*COS(AL)                                           AER13000
 9994 CONTINUE                                                          AER13010
      CLTOT=CLB                                                         AER13020
      CDTOT=CDB                                                         AER13030
      CLALW=0.                                                          AER13040
      CLALT=0.                                                          AER13050
      CDT=0.                                                            AER13060
      CDD=0.0                                                           AER13070
      CDW=0.                                                            AER13080
      CATD=0.                                                           AER13090
      CNTD=0.                                                           AER13100
      CNT=0.                                                            AER13110
      CNTP=0.                                                           AER13120
      CAT=0.                                                            AER13130
      CAW=0.                                                            AER13140
      CNW=0.                                                            AER13150
      CNWP=0.                                                           AER13160
      CLW=0.                                                            AER13170
      CLWP=0.                                                           AER13180
      CLT=0.                                                            AER13190
      CLTP=0.                                                           AER13200
      CLTT=0.                                                           AER13210
      CLI=0.                                                            AER13220
      CLWT=0.                                                           AER13230
      CLALW2=0.                                                         AER13240
      CPW2=0.                                                           AER13250
      CAW2=0.                                                           AER13260
      CNTT=0.                                                           AER13270
      CNWT=0.                                                           AER13280
      CNWT2=0.                                                          AER13290
      CNW2=0.                                                           AER13300
      CLW2=0.                                                           AER13310
      XCPW2=0.                                                          AER13320
      XCPT=0.                                                           AER13330
      XCPW=0.                                                           AER13340
      GO TO 1992                                                        AER13350
C TOTAL NORMAL,AXIAL, AND DRAG FORCE COEFFICIENTS                        AER13360
 1991 CNBC=(CLBW+CLBT+CLBW2)*COSAAL                                     AER13370
      CNTP=CLTP*COSAAL+CDT*SINAAL                                       AER13380
      CNWP=CLWP*COSAAL+CDW*SINAAL                                       AER13390
      CNW2=CLW2*COSAAL+CDW2*SINAAL                                      AER13400
      CN=CNWP+CNTP+CNB+CNW2+CNBC                                        AER13410
      CDI=CDI+CDB                                                       AER13420
      CDTOT=CDOWBT+CDI+CDTD                                             AER13430
      CA=CDTOT*COSAAL-CLTOT*SINAAL                                      AER13440
```

```
C   TOTAL CENTER OF PRESSURE CALCULATIONS
      XCPBC=(XCPBW*CLBW*COSAAL+XCPBT*CLBT*COSAAL+XCPBW2*CLBW2*COSAAL)
     1/CNBC
      IF (ST) 9901,9901,9902
 9902 XCPT=XCPTB
 9901 IF (SW) 9903,9903,9904
 9904 XCPW=XCPWB
      IF (SW2) 9903,9903,1993
 1993 XCPW2=XCPWB2
 9903 IF (SW2) 1994,1994,1995
 1994 XCPW2=0.
      CNW2=0.0
      IF(SW) 1997,1997,1995
 1995 XCPW=((XCPW)*CNWP+(XCPW2)*CNW2)/(CNWP+CNW2)
      CNWP=CNWP+CNW2
      IF (SW) 1997,1997,1998
 1997 XCPW=0.
 1998 IF (ST) 1999,1999,1996
 1999 XCPT=0.
 1996 XCP2=(CNB*XCPB+XCPT*CNTP+XCPW*CNWP+XCPBC*CNBC)/(CNB+CNTP+CNWP+CNBC
     1)
C   PITCHING MOMENT
 1992 CM=CN*(XCG2-XCP2)/XREF
      AL1=AL*57.29578
C OUTPUT
      PRINT 5002,AL1,CLTOT,CDTOT,CLWP,CLBW,CLTP,CLBT,CLB,CDI,CNWP,CNTP
     1,CLTD,CDTD,CN,CA,XCPW,XCPT,XCPB,XCP2,CM
 5002 FORMAT(1X,F3.0,18(1X,F5.2),1X,F6.2)
      ALPHA = XAL(J+1)
 6000 CONTINUE
      PRINT 69,CDINL,CDAFT,CDPROT,CDOB,CDOW,CDOT,CDMISC,CDOWBT
   69 FORMAT(//,2X,'CDINL=',F6.4,4X,'CDAFT=',F6.4,4X,'CDPROT=',F6.4,//,2
     1X,'CDOB=',F6.4,4X,'CDOW=',F6.4,4X,'CDOT=',F6.4,4X,'CDMISC=',F6.4,4
     2X,'CDOWBT=',F6.4)
      DELTA1=XDT(II+1)
 6001 CONTINUE
      VXM=XVXM(IJ+1)
 6002 CONTINUE
      IF (NBODY-IL) 3334,3334,3333
 3334 CONTINUE
      WRITE(6,55050)
55050 FORMAT(/,1X,'DO YOU WANT ANOTHER RUN, 0=YES, 1=NO')
      READ(5,1112)IZXI
      IF(IZXI.EQ.0)GO TO 55000
      STOP
      END
```

REFERENCES

1. Specifications, Soviet Aircraft, Aviation Week and Space Technology, V. 112, No. 9, p. 116, 3 March 1980.

2. New Soviet Fighters Detailed, Military Electronics and Countermeasures, V. 6, No. 5, p. 67-69, May 1980.

3. All the Worlds Missiles, General Dynamics, Pamona Division.

4. Michael Brown, F-16 Programme Heads for December First Flight, Interavia, V. XXXI, p. 104-106, February 1976.

5. Philip Geddes, Two Versions of the F-18 in Hot Competition, Interavia, V. XXXIV, p. 351-356, April 1979.

6. Advisory Group for Aerospace Research and Development Lecture Series No. 52, Guidance Law Applicability for Missile Closing, by Dr. Robert Goodstein, May 1972.

7. Rapid Approach for Missile Synthesis, Rochet Synthesis Handbook, General Dynamics, Convair Division, November 1979.

8. Merril I. Skolnik, Introduction to Radar Systems, McGraw-Hill Book Company, 1962.

9. William L. Wolfe, Handbook of Military Infrared Technology, Office of Naval Research, Department of the Navy, Washington, D.C., 1965.

10. S.S. Chin, Missile Configuration Design, McGraw-Hill Book Company, 1961.

11. Marvin E. Bachman, Terminal Ballistics, Naval Weapons Center, Research Department, February 1976.

12. Leland M. Nicolai, Fundamentals of Aircraft Design, Domicone Printing Services, 1975.

13. NACA Report 1307, Lift and Center of Pressure of Wing-Body-Tail Combinations at Subsonic, Transonic, and Supersonic Speeds, by William C. Pitts, Jack N. Nielsen, and George E. Kaattari, 1959.

14. Unpublished Notes on Rocket Propulsion, by Professor D. Netzer, September, 1980.

15. Naval Weapons Center Technical Memorandum 2953, Preliminary Solid Rocket Motor Design Techniques, by H. Platzek, p. 15, December 1975.

16. D.E. Hoak, U.S. Air Force Stability and Control Handbook (DATCOM), AF Flight Dynamics Laboratory, April 1976.

17. Naval Air Development Center Report No. 74023-30, A Digital Computer Method for Predicting Static Aerodynamic Characteristics of Typical Missile Configurations, by F.A. Kuster, Jr., 29 January 1974.

18. Naval Ship Research and Development Center Report 3645, A Method for Predicting the Static Aerodynamic Characteristics of Typical Missile Configurations for Angles of Attack to 180 Degrees, by Bernard F. Saffell, Jr., Millard L. Howard, and Eugene N. Brook, Jr., March 1971.

19. NASA Technical Note D-6996, Prediction of Static Aerodynamic Characteristics for Space-Shuttle-Like and Other Bodies at Angles of Attack From 0 to 180 Degrees, by Leland H. Jorgensen, January 1973.

20. NASA Technical Memorandum X-3309, Experimental Aerodynamic Characteristics for Slender Bodies with Thin Wings at Angles of Attack from 0 to 58 Degrees and Mach numbers from 0.6 to 2.0., by Leland H. Jorgensen and Michael H. Howell, January 1976.

21. NASA Technical Memorandum X-2780, Aerodynamic Characteristics at Mach 0.60 to 4.63 of Two Cruciform Missile Models, One Having Trapezoidal Wings with Canard Controls and the Other Having Delta Wings with Tail Controls, by William A. Corlett and Dorothy T. Howell, July 1973.

22. NASA Technical Memorandum X-2367, Longitudinal Aerodynamic Characteristics at Mach 1.50 to 4.63 of a Missile Model Employing Various Canards and A Trailing-Edge Flap Control, by Charles D. Trescot, Jr., October 1971.

23. Unpublished Notes on Weapons System Design, by Professor A. Fuhs, September 1980.

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