MULTI-DISCIPLINARY DESIGN AND OPTIMIZATION OF AIR TO SURFACE MISSILES WITH RESPECT TO FLIGHT PERFORMANCE AND RADAR CROSS SECTION

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MULTI-DISCIPLINARY DESIGN AND OPTIMIZATION OF AIR TO SURFACE MISSILES WITH RESPECT TO FLIGHT PERFORMANCE AND RADAR CROSS SECTION

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ABSTRACT

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This study focuses on the external configuration design of a tactical missile based on maximizing flight range while minimizing the radar signature which is a crucial performance parameter for survivability. It is known that shaping of a missile according to aerodynamic performance may have significant negative effects on the radar cross section. Thus, the impact of the geometry changes on the aerodynamic performance and the radar cross section is investigated. Suggorage models for the flight range, control effectiveness and the radar cross section (RCS) at an X band frequency are established by employing Genetic Algorithm. Accuracies of surrogate models are discussed in terms of statistical parameters. Seventeen geometrical parameters are considered as the design variables. Optimum combinations for the design variables are sought such that flight range is maximized while the radar cross section is minimized. The multi objective optimization problem is solved by imposing the static stability margin as a hard nonlinear constraint. Weighted sum approach is utilized to compare results with known missile configurations. Weights for flight range and Radar Cross Section are varied to obtain Pareto optimal solutions.

Keywords: Multi-Disciplinary Optimization, Radar Cross Section, External Configuration, Flight Performance, Genetic Algorithm.

ÖZ

HAVADAN KARAYA FÜZELERİN UÇUŞ PERFORMANSI VE RADAR KESİT ALANI BAKIMDAN ÇOK DİSİPLİNLİ ENİYİLENMESİ

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Tez Yöneticisi : Prof. Dr. M. Haluk Aksel

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Bu çalışma taktik bir füzenin dış geometrik parametrelerini füze uçuş menzili enyüksek, uçuşu devam ettirebilmesi için önemli bir parametre olan radar görünürlüğü de en düşük olacak şekilde tasarlamaktır. Bir füzeyi aerodinamik olarak en şekillendirmenin radar kesit alanı üzerinde olumsuz etkisi olduğu bilinmektedir. Bu yüzden geometri üzerindeki değişikliklerin aerodinamik etkileri ve radar kesit alanı üzerine olan etkileri incelenmiştir. Temsili modellerin menzil, kontrol edilebilirlik ve X bant frekansda radar kesit alanı değerleri Genetik Algoritma kullanılarak saptanmıştır. İstatistiksel parametreler kullanılarak temsili modellerin başarımı değerlendirilmiştir. Tasarım değişkenleri olarak onyedi geometrik parametre tanımlanmıştır. Tasarım değişkenlerinin eniyi konbinasyonu için menzilin enyüksek, radar kesit alanı endüşük değerinde olması istenmektedir. Bu çok amaçlı eniyileme çalışması doğrusal olmayan bir kısıt olan durağan kararlılık limiti dikkate alınarak çözülmüştür. Ağırlıklandırılmış sonuçlar bilinen füze konfigürasyonlarıyla kıyaslanmak için kullanışmıştır. Menzil ve Radar Kesit Alanı için ağırlıklar Pareto çözümler için değişiklik göstermektedir.

Anahtar Kelimeler: Çok Disiplinli Eniyileme, Radar Kesit Alanı, Dış Geometri, Kavramsal Tasarım, Uçuş Başarımı, Genetik Algoritma.

To My Parents

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ASM	Air to Surface Missile
AoA	Angle of Attck
q	Angular speed in body-y axis
C_A	Axial force coefficient
X_{CP}	Axial location of pressure center
X_{CG}	Axial location of the center of gravity
u	Axial speed in body axis
CG	Center of Gravity
CFD	Computitional Fluid Dynamics
DOF	Degree Of Freedom
$Cm_{\delta e}$	Derivative of aerodynamic moment coefficient with respect to fin deflection
DOE	Design Of Experiments
C_{nb}	Directional stability
D	Drag force acting on missile body
C_D	Drag force coefficient
C_{lb}	Effective dihedral
F_x	Force in x-axis
F_y	Force in y-axis
m_f	Fuel mass

GA	Genetic Algorithm
g_0	Gravitational acceleration
L	Lift force acting on missile body
C_L	Lift force coefficient
L/D	Lift to Drag Ratio
n	Load factor
$C_{m\alpha}$	Longitudinal stability term
I_{yy}	Moment of inertia about y-axis
C_N	Normal force coefficient
M	Pitch moment acting on missile body
C_m	Pitch moment coefficient
RCS	Radar Cross Section
S	Reference area
d	Reference diameter
Re	Reynolds Number
C_r	Root Chord
b	Span
I_{sp}	Specific impulse
$\bar{x}$	The design vector including the geometry parameters
T	Thrust force
C_t	Tip Chord
w	Vertical speed in body axis
W	Weight of the missile
α	Angle of attack

β	Sideslip angle
γ	Flight path angle
δ_1	Deflection angle of the first tail
δ_2	Deflection angle of the second tail
δ_3	Deflection angle of the third tail
δ_4	Deflection angle of the fourth tail
δ_e	Elevator deflection angle
θ	Pitch Angle
Λ	Sweep Angle
ρ	Air density

CHAPTER 1

INTRODUCTION

1.1 Background

In the missile designing studies, calculating the performances of axisymmetric (circular) body cross-sectional shape missiles over a wide range of flight conditions have been taken great place. Because of the recent defense strategies, tactical missile systems have had increasing requirements for more efficient storage and carriage, higher angle of attack performance, lower radar cross-sectional area and longer range [1]. The desire to increase weapon range and maneuverability, to design weapons which are more optimum total drag, storage, range, and radar signature standpoint has driven designers to consider study on multi-disciplinary optimization studies including above disciplines and including axisymmetric and nonaxisymmetric body shapes.

1.2 Classification of Missiles

Launch platform and mission profile, propulsion system, guidance, control and trim systems can classify the missiles. An important classification on the basis of points of Launch platform and mission profile is given in Figure 1.1. Another basis of feature among missiles is the guidance system. In a command system the missile and the target are continuously tracked from one or more vantage points, and the necessary path for the missile to intercept the target is computed and relayed to the missile by some means such as radio. A beam-riding missile contains a guidance system to constrain it to a beam. The beam is usually radar illuminating the target. Thus, if the missile stays in the beam, it will move toward the target. A homing missile has a seeker, which sees the target and gives the necessary directions to the missile to intercept the target. The homing missile can be subdivided into classes having active, semiactive, and passive guidance systems. In the active class the missile illuminates the target and receives the reflected signals. In the semiactive class the missile receives reflected signals from a target illuminated by means external to the missile. The passive type of guidance system depends on a receiver in the missile sensitive to the radiation of the target itself [2].

Trajectory type of missiles is another method of classification. Missiles could be divided into some main trajectory classes such as ballistic missiles, glide missiles, skip missiles and tactical missiles. This is highly related with mission profile of missile. For instance, a ballistic missile has a ballistic trajectory which fallows ballistic mission profile and a glide missile is launched from an altitude and starts glides down on the target.

Missiles can also be classified according to their propulsion systems; turbojet, ram-jet, rocket, etc. Most of the air-to-surface missiles in the literature are turbojet powered missile because of its high range and reliability. In this study, to design and optimization of an air-to-surface missile, turbojet powered propulsion system is selected.

Furthermore, trim and control mechanisms of missiles make differentiations among missiles. Missiles can be controlled by deflecting their control surfaces such as canards, wings or tails. Control surfaces also used for trim condition. Because canards and wings are mostly main lifting surfaces, the wing and missile controlled missiles have smaller control surfaces than tail controlled missiles. Lifting surface must be as smooth as possible and as long as possible for high lift to drag ratio and high maneuverability especially for air-to-air and air-to-surface missiles. In this study, for an air-to-surface missile with necessarity of high maneuverability, tails are selected to be control surfaces and wings are selected to be control devices.

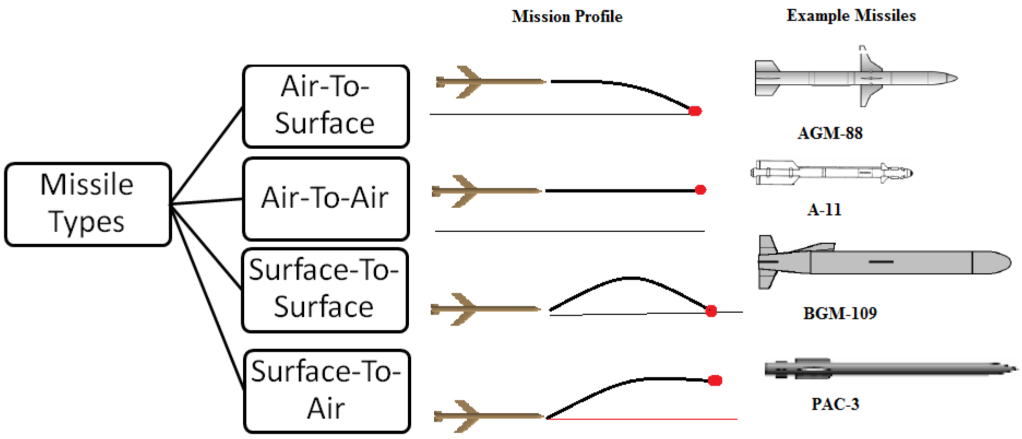


Figure 1.1 Launching and impact classifications of missile systems

1.3 Literature Survey

This study is a multi-disciplinary study and the concept includes wide designing areas and difficult to investigate in one section so literature study is investigated in some subparts as multi-disciplinary optimization studies, axisymmetric and symmetric missiles cross sectional missiles, studies on Radar Cross Section (RCS) and flight performance analyses of missile systems.

1.3.1 Multi Disciplinary Optimization

In traditional missile preliminary design problems, one objective function of one discipline is analyzed and minimized. Nevertheless, in missile engineering it is not sufficient to find optimum configuration of missile of desired mission profile and modern war requirements. That's why the designers decide to use multi-disciplinary studies in aerospace and defense studies. Specifically thinking on missile studies, there are lots of conflicting objectives. For instance, missile Radar Cross Section (RCS) value always tends to be minimized while missile lift to drag ratio is tried to be maximized.

It is presented a bidisiplinary optimization problem by Zhu, in 1993. The study includes aerodynamics and electromagnetic optimization for a wing profile. It is used Euler solver for flow field and a time domain Maxwell equations solver for the electromagnetic field to analyze all design models. Figure 1.2 shows radar cross section evaluations with respect to view angle [3].

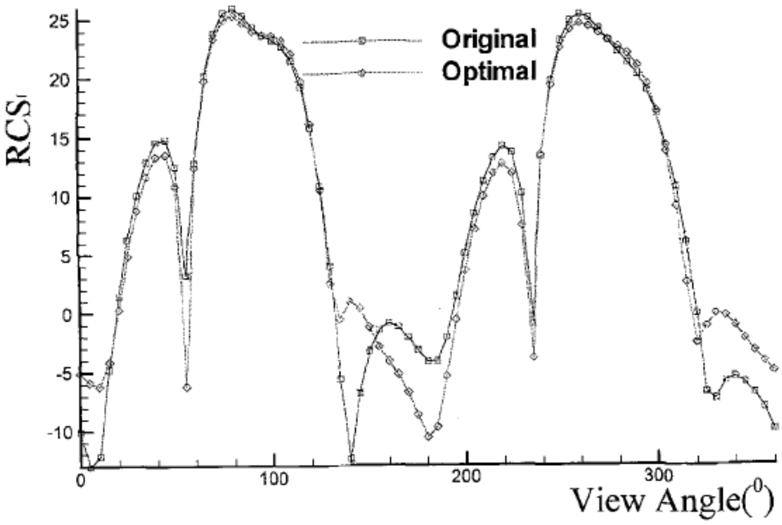


Figure 1.2 Comparison of Results of RCS minimization [3]

Also Raino studied on similar bi-disciplinary optimization problem with Zhu. Rania studied on two-dimensional airfoil multi-disciplinary optimization problem. He obtained an approximation for Pareto set for optimal solutions by using Genetic Algorithm (GA). Drag coefficients and integral of the transverse magnetic radar cross section over a given sector are the objective functions of his study. In this study, drag coefficient approximations is based on Computational Fluid Dynamics (CFD) analyses which use finite volume discritization of inviscid Euler equations. And the second objective, RCS is obtained by computational electromagnetic (CEM) wave field analysis requires the solutions of a two dimensional Helmholtz equation which is obtained using a fictitious domain method. The results of that study shows that the number of performed cost function evaluations was rather high and so the optimization was computationally expensive. In order to reduce the amount of computations, the convergence criteria of set of Pareto optimal solutions should be improved in their optimization algorithm. Some results of Pareto set of optimal solutions are seen from Figure 1.3 [4].

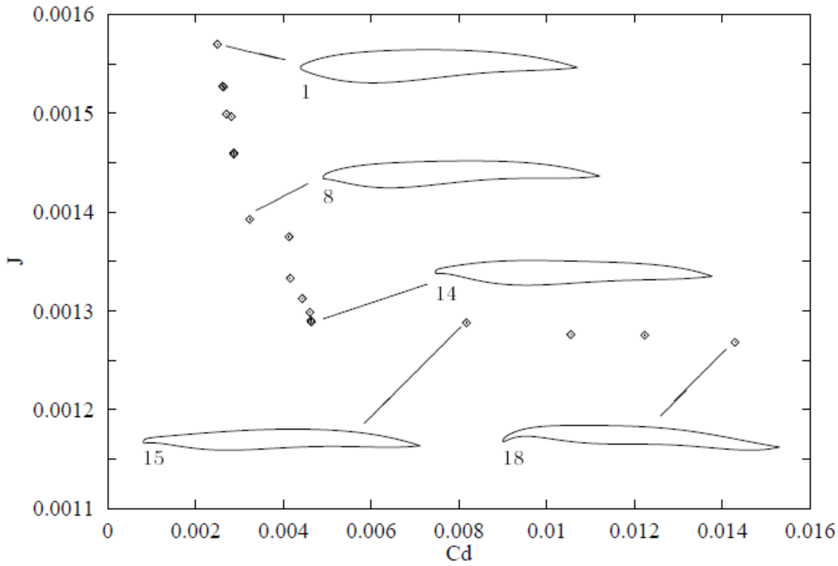


Figure 1.3 Wing profile optimization results [4]

In additions to these studies, Lee studied on a robust evolutionary algorithm to optimize an unmanned (combat) Aerial Vehicles (UCAV). Study is aimed for airfoil sections and wing plan form shape design optimization for the improvement of aerodynamic performance and the reduction of RCS. The results of optimizations exemplify that to improve the aerodynamic efficiency evolutionary optimization methods can be used for transonic wing airfoil sections. Results also indicate that optimal and pareto non-dominated solutions are efficiently produced [5].

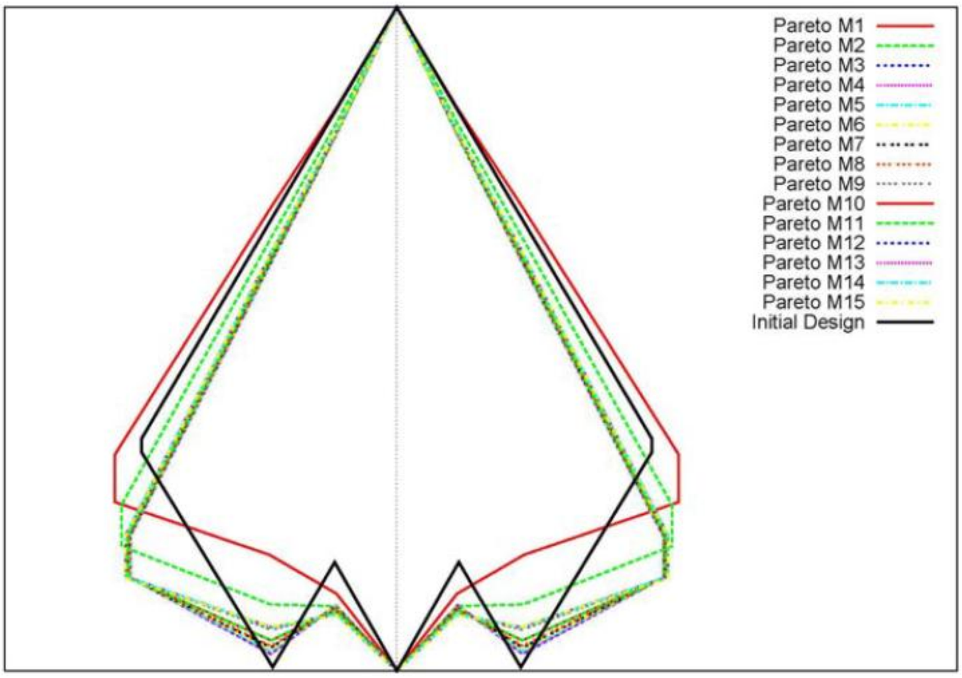


Figure 1.4 Pareto set of optimal solutions [5]

1.3.2 Axisymmetric and Symmetric Missiles

In literature, studies on missile cross section are mostly investigated with respect to aerodynamic efficiency. Studies which concern a multi-disciplinary optimization approach on just missile body cross sections are not investigated. Thus, in this section, literature study focused on surveys defining the baseline circular and noncircular missile body cross sectional geometry. Most studies compare aerodynamic efficiency of alternative designs as circular and noncircular cross sectional missiles. Aerodynamics is the most important issue for missile preliminary design phase [1]. So, the alternative designs were firstly evaluated with respect to aerodynamically effectiveness and stability performances.

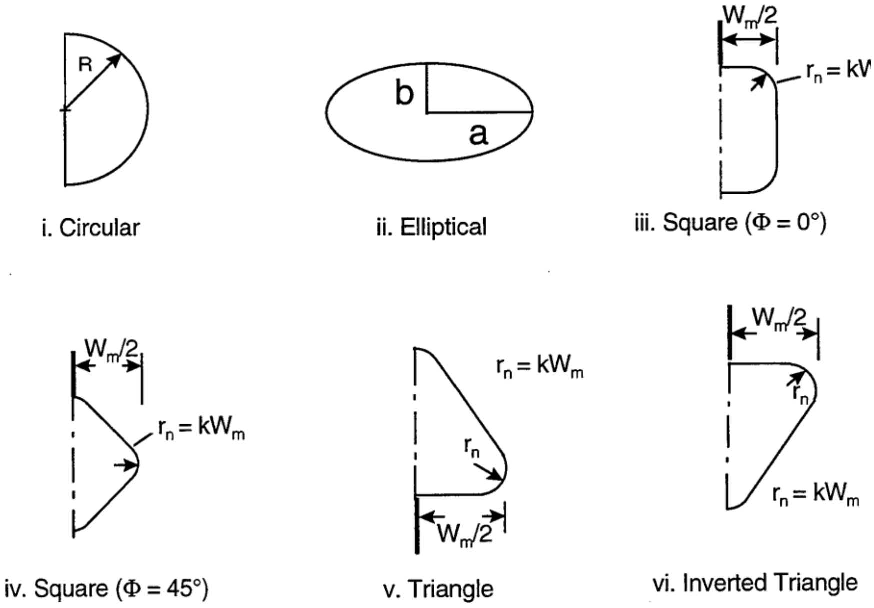


Figure 1.5 Circular, elliptical, square and triangular body cross-sectional shape of interest [6]

Non-circular cross-section missiles are mostly elliptical. And the other rare applications in the literature are square, diamond and triangular shaped ones. Figure 1.5 gives some examples of these configurations [6]. There are also complex body cross-sectional shapes which are of interest in preliminary design tradeoffs because of unknown aerodynamics and having hard producing requirements. In preliminary tradeoffs and literatures there is lack of interest in complex body shapes such as waveriders, monoplanar and nonplanar missiles, lifting bodies and other complex configuration missiles which are mainly derived from elliptically shaped cross sections.

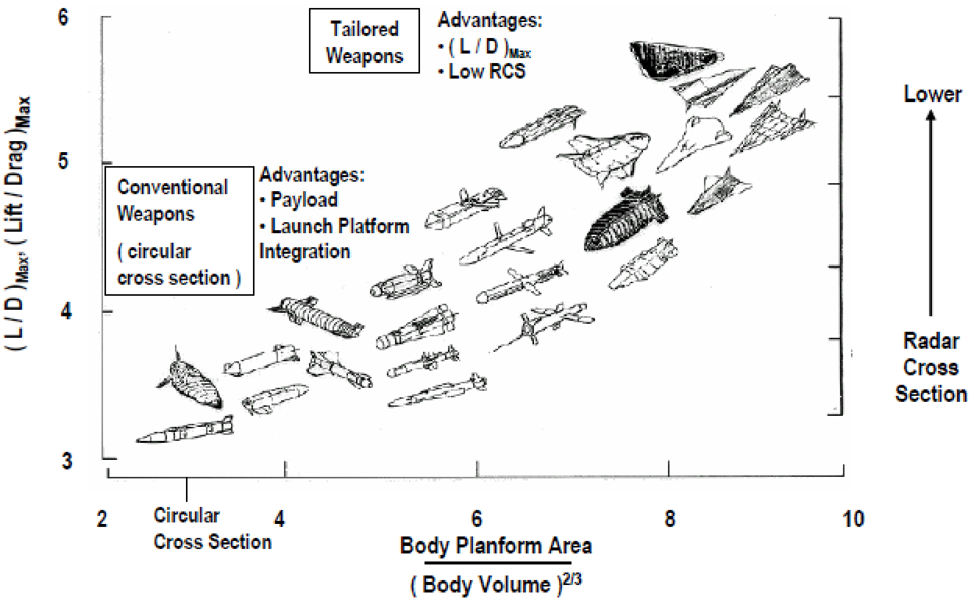


Figure 1.6 Trade-off of low observables and $(L/D)_{max}$ vs volumetric efficiency [1]

Figure 1.6 compares weapon configurations that have conventional cylindrical bodies of circular cross-section to other weapons that are highly tailored, using aerodynamic shaping of their lifting body configurations.

In the literature the most common non-circular cross-section missiles are categorized such general types, which are as defined before elliptical and the others such as square, diamond and triangle cross-section missiles. Studies on elliptically shaped configurations also grouped as elliptical, elliptical monoplanes, waveriders, and the last one is lifting body missiles includes highly tailored elliptical cross-sections. Advantages and disadvantages of these configurations will be given by investigating literature studies, and though this evaluation the requirements of missile cross-section will be stated at the end of the section.

Chin stated in 1961 that the external geometry of missile includes three main division, missile nose, missile mid-body and boottail. Nose of missile are ogival for most of the air-to-surface applications but some missile have also conical or power series type of nose. In most missile configurations, the mid-section is cylindrical in shape. This shape is advantageous from the standpoints of drag, ease of manufacturing, and load-carrying capability [7]. Because of 1961's technology level, in the manufacturing process, design and analyze tools, circular cross-section configuration was seen to be the best solution but following studies did not draw the same picture.

After 17 years from Chin, Nielsen stated that as a result of future trends as advances in the computer technology and manufacturing area in tactical missiles, a number of new concepts are being advanced to fill the needs. These configurations include noncircular bodies, waveriders, airbreathing engines, monoplanar and non-planar missiles etc. In his works, some of these subjects, which are focused mostly on missile cross-section, has been covered from a general point of view [2].

Jackson and Sawyer stated that special areas including bodies with noncircular cross sections and bank-to-turn missiles are necessary to achieve the desired aerodynamic efficiency and effective integration of the air induction system. Some of his studies are oriented primarily toward the missile application of noncircular bodies and the more recent developments in bank-to-turn missile configuration aerodynamics. According to Jackson and Sawyer, missile bodies with square/rectangular or diamond cross-sectional shapes should be studied primarily because of their advantages in packaging and submunition deployment. These shapes are ideal for packaging but have aerodynamic characteristics which are extremely sensitive to orientation. Extensive experimental studies of this class of missile bodies have been made. The severe separation effects associated with the corners of the square or rectangular cross-sectional shapes result in undesirable aerodynamic stability characteristics that are difficult to predict. Much of the work in this area has been to examine the effects of corner radius on the square section in an effort to alleviate the undesirable corner effects. Typical experimental studies of the effects of corner radius on missile shapes with square cross sections (Figure 1.7) show a general reduction or normal force and less effect of roll angle with increase in corner radius [8].

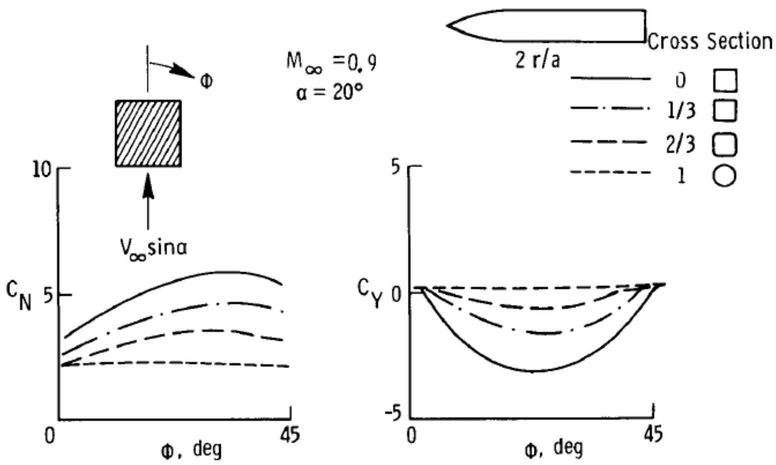


Figure 1.7 General reduction or normal force and less effect of roll angle with increase in corner radius [8]

Moore also studied on wing-body configurations of square cross-sectional shaped bodies which are given in Figure 1.8 and results and wind tunnel data are given in Figure 1.9. Studies were repeated with the bodies rolled 45 degrees into the diamond configuration. The fins were mounted on the corners of the body in all cases so that in the square roll position, the fins are in an “x” or cross-position; and in the diamond cases, the fins are in a "+" or plus roll position. The Mach number was kept constant at 0.75 [6].

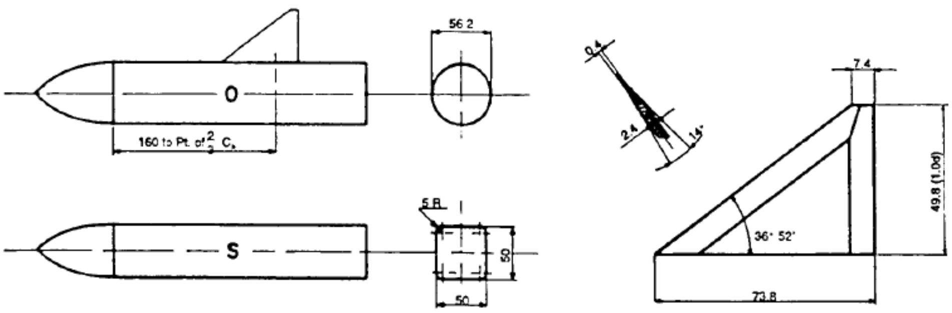


Figure 1.8 Moore's wing-body configurations having square and circular cross-sectional shapes [6]

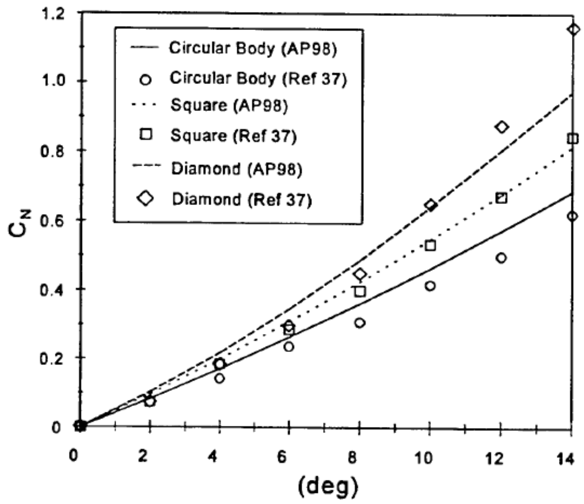


Figure 1.9 Normal force coefficients for squares (k=0.1) and diamonds (k=0.1) compared to circular body at M=0.75 [6]

The results of the entire data show that the aerodynamically most efficient is the triangular shaped missiles between circular, square, diamond, triangular and inverted triangular shaped missiles. The situation didn't change by Mach number variation. Also for the wing-body configurations the same rule is true for the diamond bodies because of the lack of data for triangular cross-sectional body trough the data from Figure 1.9.

Jackson and Sawyer also stated that noncircular missile cross-sectional shapes have been considered primarily for improved storage and carriage. To achieve this aim, improved aerodynamic efficiency associated with monoplanar missile configurations should also been considered. Elliptical cross-sectional shapes have been studied extensively as candidates for monoplanar missile configurations by Jackson and Sawyer [8].

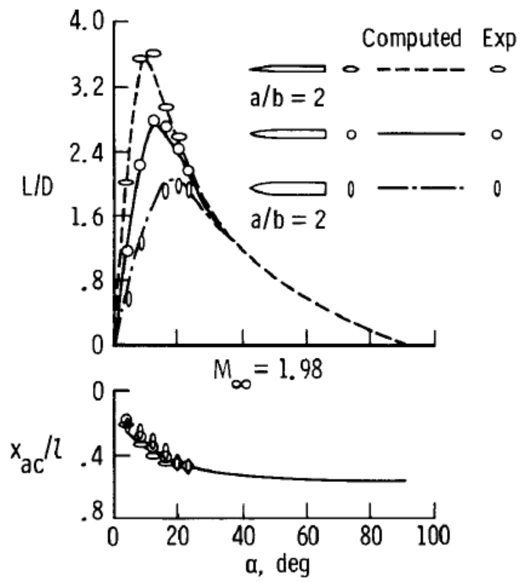


Figure 1.10 Comparison of computed with experimental aerodynamic characteristics for bodies with elliptic cross sections (*L/D*=10, *Re*=6.7x106) [8]

As indicated in Figure 1.10, the aerodynamic efficiency is greatly improved by going from a circular cross section to a 2:1 horizontal ellipse. Internal packaging, volume, and structural considerations were not greatly compromised. In addition, elliptical cross-section shapes can, by virtue of their low profile, improve carriage drag [8].

Also, the work of Graves, which was performed for a wide range of Mach numbers (from subsonic to supersonic) around elliptic and circular cross-sectional bodies showed similar results. The aerodynamic advantages of missile bodies with elliptical cross sections are clearly indicated in his work. This work makes direct comparisons of performance, stability, and control of missile configurations with Haacka-Adam longitudinal area distributions and circular vs. 3:1 ellipse cross sections. The aerodynamic performance potential both at cruise and during maneuver is indicated by the maximum lift to drag ratio (*L/D*) shown in Figure 1.11 [9].

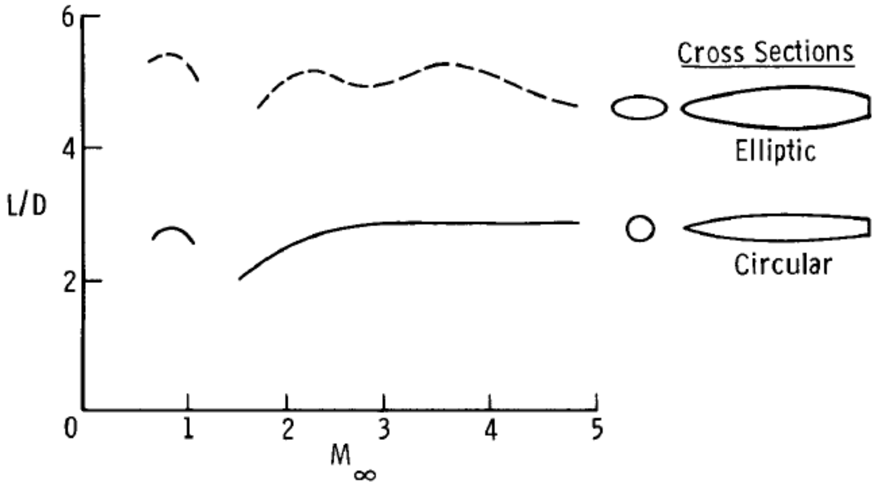


Figure 1.11 Comparison of maximum lift-to-drag ratio for Haack-adam body with circular and elliptic cross sections [9]

The large increase in *L/D* over the Mach number range from subsonic to hypersonic speeds indicates a major advantage of noncircular monoplanar body shapes. In addition to the *L/D* performance advantages, Graves showed significant lateral-directional stability advantages of bodies with elliptic cross sections [9].

Also Nielsen stated that a circular body can develop rolling moments by skin friction but they are of small magnitude. It thus has zero effective dihedral $C_{l\beta}$. A noncircular body under sideslip can have rolling moment and side a force as a result of pressure forces, yielding finite values of $C_{l\beta}$ and $C_{n\beta}$. Figure 1.12 shows the effective dihedral and directional stability of an elliptical body as compared to a circular one of the same area distribution. Note that the elliptical body has good effective dihedral while the circular body has neutral stability. Both bodies have poor directional stability, but the elliptical body is less unstable than the circular body and will thus require a smaller vertical fin [10].

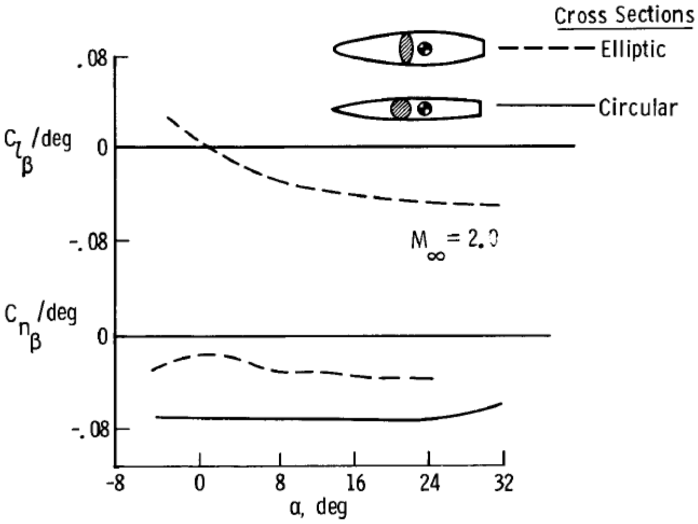


Figure 1.12 Comparison of lateral directional stability for Haack-Adams body with circular and elliptic cross sections [11]

Jackson and Sawyer pointed out that it is important to recognize that these stability characteristics are advantageous only if the missile is in the bank-to-turn guidance mode [8].

Nielsen stated that an elliptic missile on a noncircular body represents an interesting new design possibility which can have different stability and control than the usual cruciform missile. The stability and control characteristics of monoplanes with elliptical bodies generally provide a good balance between longitudinal and lateral-directional stabilities. If a profile is too low, it can reduce the directional stability. It also causes unsporting of controls at high deflections with an attendant loss of control [10].

Many of the existing studies of the effect of cross-sectional shape on missile aerodynamics consider only missile bodies with constant cross-sectional shape over the length of the body. Practical missile configurations, however, can require circular nose and afterbody cross-sectional shapes to satisfy seeker requirements and efficient nozzle configurations. A generic study or elliptic cross-sectional body shape with hemispherical noses and circular bases was conducted by Graves and Fournier. A summary of these results is presented in Figure 1.12. A significant effect of afterbody shape can be seen on the aerodynamic characteristics of these shapes [11].

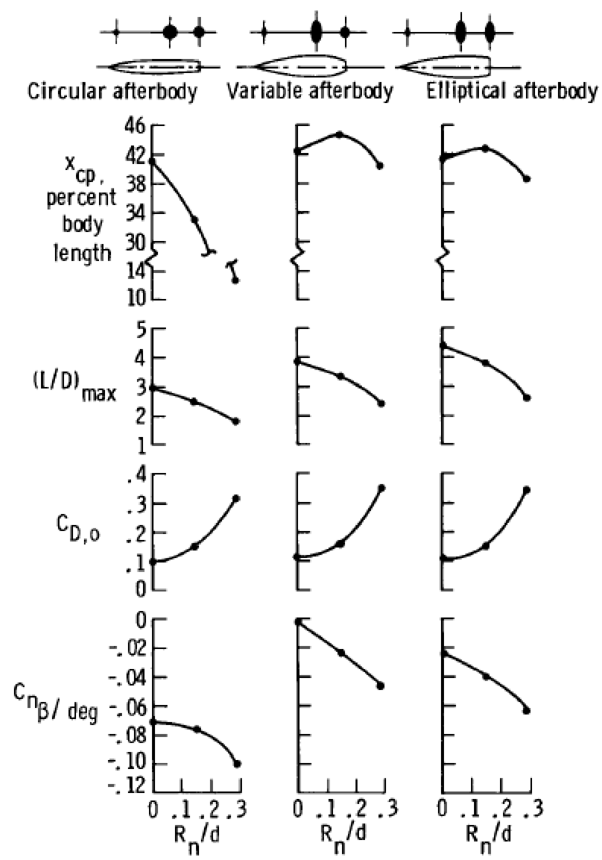


Figure 1.13 Aerodynamic effects of cross-section variation on missile bodies [11]

Also Moore's study includes elliptical cross sectional shapes with *a/b* from 0.5 to 3.0, Mach numbers varying from 0.6 to 2, and angle of attack as high as 58 degrees, and some cases with wings. Figure 1.14 indicates results of these studies [6].

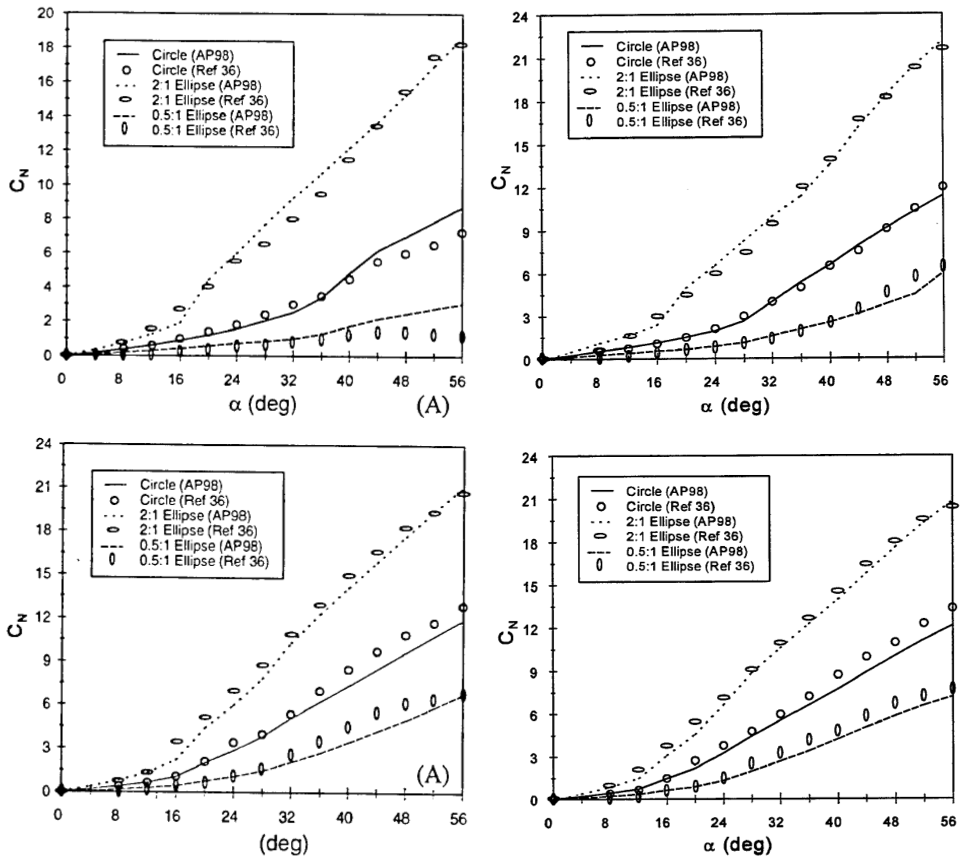


Figure 1.14 Normal force coefficients for 2:1 and 0.5:1 ellipses of compared to circular body at *M*: 0.6, 0.9, 1.2, 1.5 [6]

From Figure 1.14, it is specified that 2:1 elliptic cross-section shaped configurations gave better results with respect to C_N than circular and other elliptical missiles especially at high angle of attack degrees [6].

Jackson and Sawyer experimentally investigated bodies with elliptical cross-sections and noticed a considerable increase in aerodynamic efficiency (*L/D*) for horizontal elliptical cross-sections (compared with circular cross-sections) [12].

Also Sharma investigated both computationally and experimentally a similar problem. His results not only support the previous findings, but also show increase in C_N and C_M (for horizontal elliptical cross-sections). In addition, they indicate that, in any angle of attack, by increasing ellipticity ratio, the aerodynamic efficiency is increased [13].

Recently Fleeman stated that, as shown in Figure 1.15, the maximum normal force of an elliptic body is higher than that of an axisymmetric body. The normal force coefficient of a slender body is a function only of angle of attack and body geometry and is independent of Mach number. The normal force prediction is based on combining slender body theory and body cross flow theory [14], [15]. It is valid for a body fineness ratio $L/D > 5$. For an elliptical cross section, an equivalent diameter is based on a circular cross section of the same area. Figure 1.15 shows that the normal force coefficient increases with α (up to α = 90 degrees) and a/b. As an example, at 90 degrees angle of attack, the normal force coefficient for an elliptical cross section with a major-to-minor axis ratio of $a/b = 2$ is twice that of a circular cross section. Tail dimensions are determined using the body nornam force versus angle of attack slope. The curve slope defines the static stability of missile which used in sizing tail (Figure 1.15). $C_{N\alpha}$ is the derivative of the equation for body normal force coefficient [1].

At low angle of attack,

$$C_{N\alpha(body)} = 2\,[(a/b)\,cos\,(2\phi) + (b/a)\sin\,(2\phi)] \quad (1.1)$$

with the units of per radian the equation for aerodynamic efficiency is

$$L/D = C_L/C_D = (C_N cos\alpha - C_{D0} sin\alpha)/(C_N sin\alpha + C_{D0} cos\alpha) \quad (1.2)$$

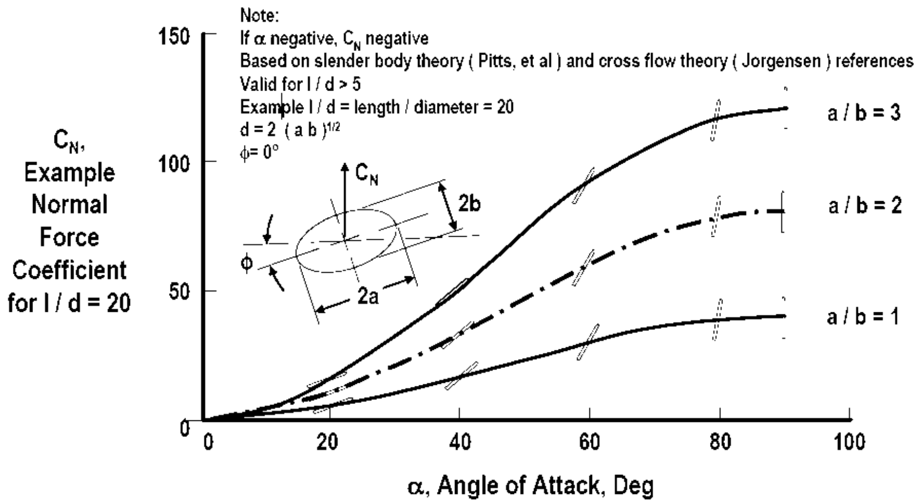


Figure 1.15 Elliptical body has higher normal force [1]

Fleeman also stated that, for an elliptic body missile without wings, the equation for the normal force coefficient is given by,

$$C_N=[(a/b)\cos(2\varphi) + (b/a)\sin(2\varphi)]\ [\sin(2\alpha)\cos(\alpha/2) + 2(L/D)\sin(2\alpha)] \quad (1.3)$$

Again, C_N for a body is based on combining slender body theory with cross flow theory. As shown in Figure 1.16, an increase in *L/D* is achievable by reducing the zero-lift drag coefficient, increasing the body fineness, and providing a elliptic body configuration (*a/b* > 1). Also shown is that as a higher *L/D* is achieved, the angle of attack in which $(L/D)_{max}$ is achieved is decreased. Furthermore, other design considerations, such as launch platform lateral and length constraints, may limit the aerodynamic shaping. Also for 1-g, constant altitude flight the angle of attack is usually much lower than the angle of attack for $(L/D)_{max}$. As a result, the *L/D* during the flyout of most rocket powered missiles is usually much lower than $(L/D)_{max}$. Although an elliptic body configuration has a higher $(L/D)_{max}$ than a circular cross section configuration, for 1-g flight at low angles of attack a circular configuration provides comparable *L/D*. Figure 1.17 compares the *L/D* of a lifting body configuration (*a/b* = 2) with that of a circular cross section (*a/b* =1) configuration. Typical values are given for a precision strike missile configuration of 2 ft^2 cross sectional area and 2,000 lb weight. As before, the *L/D* is based on combining slender body theory with cross flow theory. Maximum *L/D* for the lifting body configuration occurs at a dynamic pressure $q \approx 500$ psf. At $q = 500$ psf, the lifting body *L/D* is 40% higher than the circular cross section body (Figure 1.17) [1].

Also it is definitely stated by Fleeman that the circular body cross section configuration provides comparable *L/D* if the dynamic pressure is greater than 5,000 psf. At $q = 5{,}000$ psf, the elliptic body *L/D* is only 5% higher than the circular cross section body (Figure 1.17) [1].

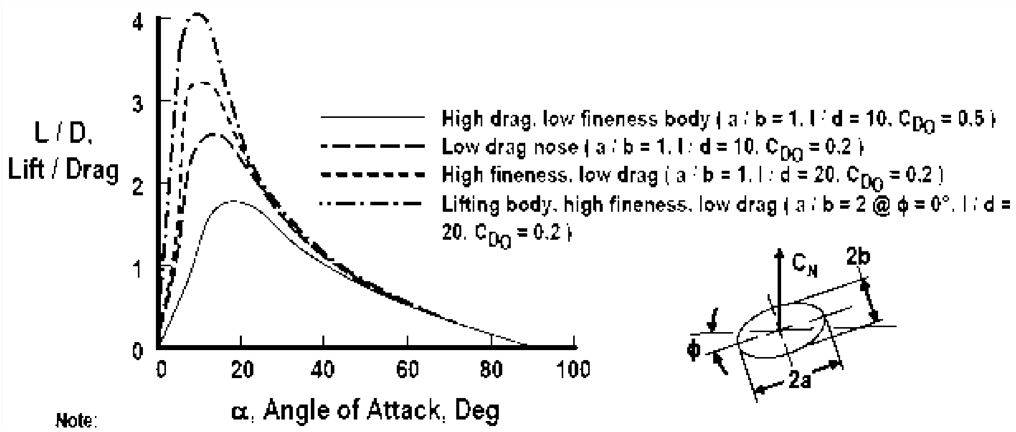


Figure 1.16 L/D ratios of elliptic lifting body cross section geometry [1]

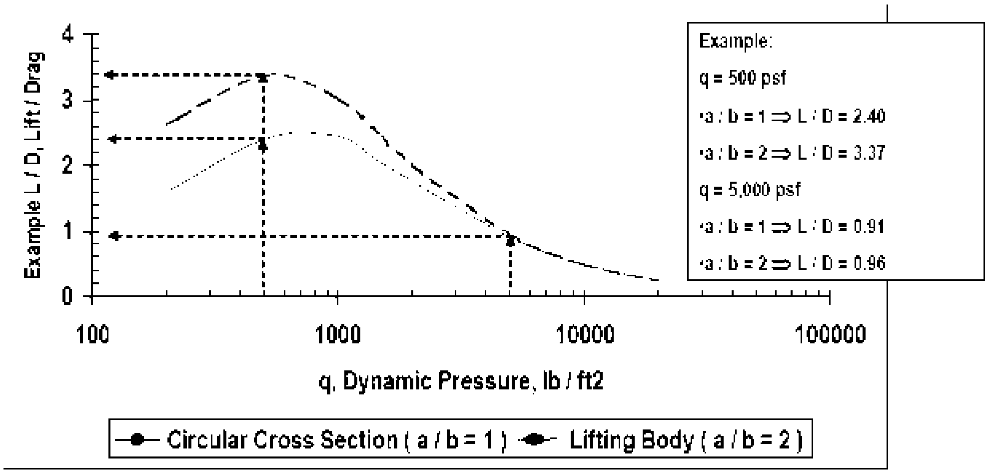


Figure 1.17 Dynamic pressure to L/D ratios of elliptically shaped body [1]

Also it is stated by Chatzigeorgiadis that, curvature surfaces increase the radar signature so circular missiles and elliptically shaped missiles show similar behavior from this point of view [16].

Nielsen stated that a monoplanar wing in connection with an elliptical body (Figure 1.18) is a good candidate for a maneuvering missile such as required in air defense or air combat missions. Its high *L/D* makes it a good candidate for longer range air-to-surface missions. The stability and control characteristics of monoplanes with elliptical bodies generally provide a good balance between longitudinal and lateral-directional stabilities.

Hunt and his coworkers have studied hypersonic missile airframes capable of housing a scramjet engine. The studies showed engine/airframe integration to be a significant problem for this class of missiles. Also the engine can have a significant effect on the missile's stability and control [17].

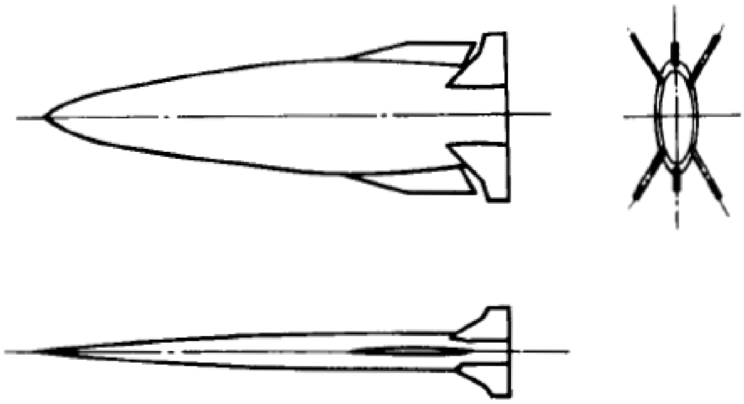


Figure 1.18 Monoplanar missile with elliptical body [2]

The term waverider was originally applied to inversely designed configurations because they inherently ride on a planar or conical shock wave. Upper surface of waverider consists of two triangular planes Joined at a hinge line. At the design condition, the hinge line is parallel to the freestream direction, and no pressure exists on the upper surfaces. This property tends to make the pressure relatively high on the lower surfaces. In addition, the upper surfaces can be formed by streamwise planes. In general, lifting surfaces at an angle of attack derive their lift from a pressure differential between the lower and upper contours. At low subsonic speeds, most of the force comes from suction on the upper surface but as the speed increases the high pressure on the lower surface becomes dominant. The properties of waveriders are therefore favorable to high performance at hypersonic speeds. The missile designer is concerned with the performance of the vehicle rather than with the means by which it is calculated; therefore the favorable attributes of waverider configurations have been adopted for configurations that are not designed to fit known flow fields but are designed to adapt the advantages of waverider characteristics to the constraints of missile operation [8].

Waveriders have higher L/D ratios at hypersonic speeds than the usual cruciform missiles by about a factor of 2. Waveriders were seriously considered for designs of hypersonic aircraft by Kucheman and his associates in England about 25 years ago. It is only recently that waveriders have been given serious attention for hypersonic tactical missiles [18].

A large range of waverider configurations is possible in Schincdel's study. The use of waveriders as missiles brings a series of aerodynamic problems such as adding a propulsion system, controls, and a radome to the basic waverider, hopefully without seriously degrading *(L/D)max*, It is clear that considering the large number of waverider configurations and the above aerodynamic problems, a large and fruitful opportunity exists for research and development in this field [19].

An interesting study in the optimization of hypersonic waveriders is declared by Bowcutt. In this study, a class of waveriders was optimized for maximum *L/D* ratio considering skin friction and blunt leading-edge drag at *M*=6 and *L/D* over 8 was calculated and at *M*=25 an *L/D* of about 4.5 was calculated [20].

One virtue of the conical waverider is that its center of pressure remains constant at supersonic speed as long as the flow is attached [10].

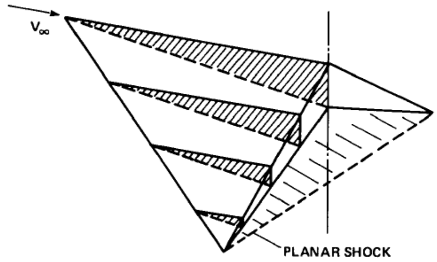


Figure 1.19 Sketch of a simple waverider [10]

Jakson and Sawyer stated that, one of the major advantages of a bank-to-turn missile is the increase in aerodynamic maneuverability and range performance. Bank-to-turn missiles have monoplanar airplane-like shapes that generally provide good aerodynamic *L/D* performance and require a balance between pitch and lateral control for maneuverability. The airplane aerodynamicist has used configuration *L/D* as the standard measure of aerodynamic efficiency. Many studies have been made to develop a practical upper bound for this important parameter.

Spearman's applicant for a lifting body tactical missile capable of high speed, low altitude overflight with downward spray of warhead fragments is the thick delta wing and a semi-conical body with delta wings. This configuration, being small and slender, is difficult to detect. High-speed, high-altitude concepts with good aerodynamic efficiency for volume and range are a possible approach to strategic penetration [21]. Spearman's objective was also point to the types of mission suitable for various configurations. The requirements for various missions include full load carrying capability, low drag, low detectability, ease of carriage and stowage, low cost, etc. The parasol wing concept appears to be applicable to this mission. It provides high-lift capability at low angle of attack by utilizing favorable interference flow fields. Spearman analyzed the aerodynamics of some unconventional missiles and considers their applicability to certain missions. The classes of missiles considered are: delta-wing bodies of Figure 1.20, and monoplanar missile as mentioned before with circular/elliptical body of Figure 1.18 [21].

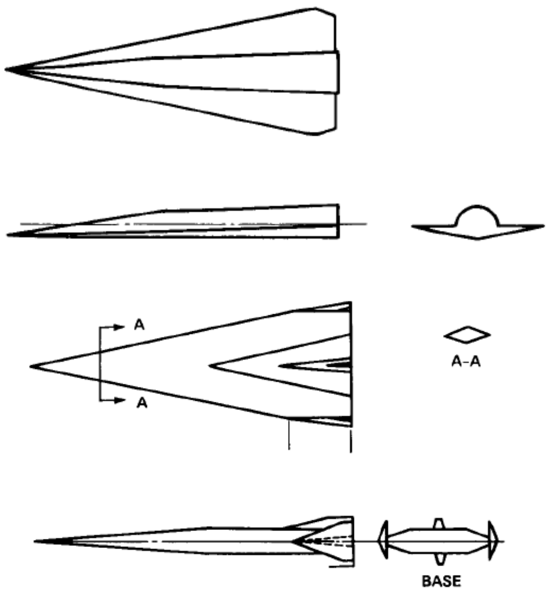


Figure 1.20 Semiconical body with delta wing (left) and thick delta wing concept [21]

Fleeman stated that a tailored elliptic body (e.g., $a/b > 2$) or adding a wing increases $(L/D)_{max}$, reduces $\alpha(L/D)_{max}$, and reduces $q(L/D)_{max}$. For example, the rocket baseline has a relatively high *L/D*, because of its wing. At Mach of 0.8, $(L/D)_{max}$ = 6.2, $\alpha(L/D)_{max}$ = 4.5 deg, and $q(L/D)_{max}$ = 350 psf. Supersonic missiles usually fly at a dynamic pressure greater than 1,000 psf. The *L/D* for a supersonic missile in 1-g flight is usually much less than $(L/D)_{max}$. As an example, the rocket baseline during 1-g powered flight at a Mach of 2, 20000 ft altitude has an *L/D* = 0.41. Figure 1.6 compares weapon configurations that have conventional cylindrical bodies of circular cross-section to other weapons that are highly tailored, using aerodynamic shaping of their lifting body configurations. An indication of subsystems packaging efficiency is the ratio of body planform area to the 2/3 power of the body volume. For a circular cross section body, this parameter has a value of about 3. As shown in the Figure 1.21, a highly tailored missile could have a value of the subsystems packaging efficiency parameter that is more than 9. An advantage of a tailored lifting body missile is higher aerodynamic efficiency *L/D*, for extended range cruise performance and enhanced maneuverability. Also shown is the synergy of tailored missiles with reduced radar cross section. Disadvantages of tailored missiles include their relative inefficiency for solid subsystems packaging and an adverse impact on launch platform integration, because of a larger span. Improved methods and tests are required for the prediction of the aerodynamics and the structural loads of non-axisymmetric weapons. This includes more extensive wind tunnel tests, computational fluid dynamics predictions, and finite element modeling of structural integrity.

An empirical (*L/D*) upper bound developed by Kuchemann and Weber is shown in Figure 1.21 along with some (*L/D*) values for typical aircraft from their study. The upper bound for aircraft aerodynamic performance is useful as a reference figure of merit in the study of bank-to-turn missile configuration performance. Because of the volume requirements of typical missiles, the aerodynamic performance generally will be lower than any upper bound established for aircraft configurations [18].

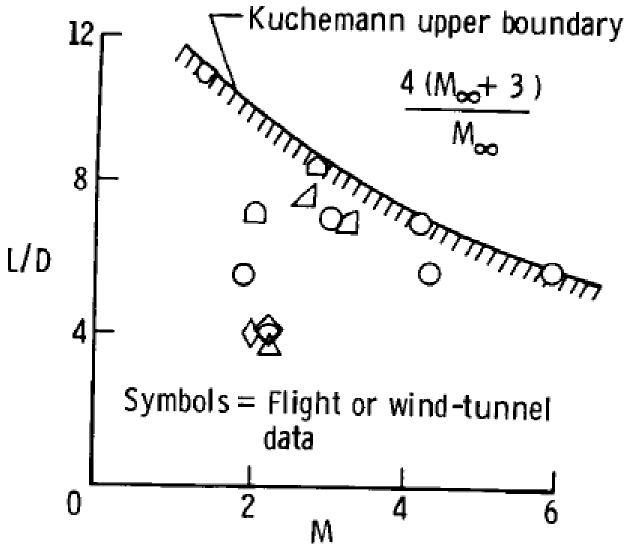


Figure 1.21 Summary of lift-to-drag ratio performance for several existing and study aircraft [18]

A significant study was made by Krieger in which aerodynamic configuration shaping was investigated as a method of improving missile cruise and maneuvering performance. In this study, several combinations of basic shapes were evaluated initially without constraints. The data of Figure 1.22 also show that among the shapes evaluated little effect or vehicle orientation was evident, and, in addition blended bodies always had better *L/D* values than wing-body configurations. It is significant to note that the unconstrained configurations or Figure 1.22 have *L/D* values that approach the Kuchemann upper bound. These configurations are of low volume ($V^{1/2}/S$ <0.3) It is also important to realize that current missile configurations (circular cylinders with cruciform fins) have values of $(L/D)_{max}$ near 3.0 at these Mach numbers and a volume-to-planform ratio ($V^{1/2}/S$) of approximately 0.4 [22].

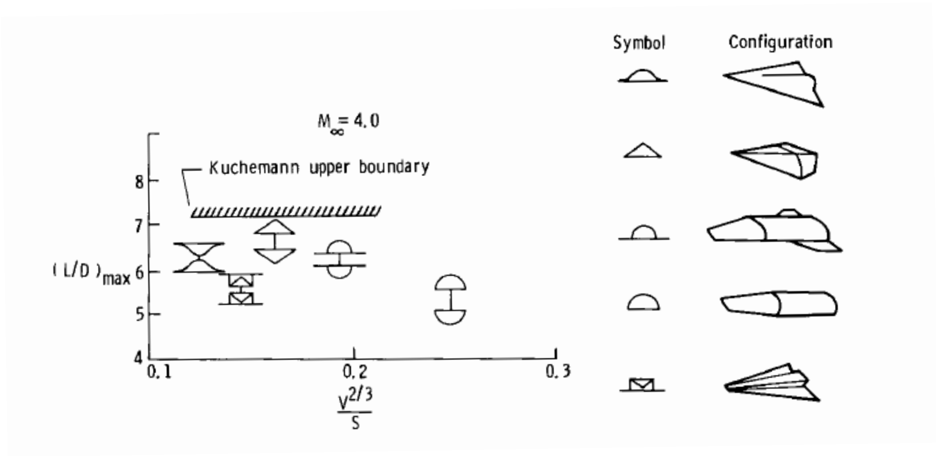


Figure 1.22 Shape effects on monoplanar missile concepts with and without wings [22]

The *L/D* ratio at maneuver conditions is an effective measure of aerodynamic maneuvering performance of a missile. A comparison of this parameter for the configurations is presented as a function of planform area in Figure 1.23. The configuration shapes include rectangular, triangular, half-ellipse, blended bodies, wing bodies, and lifting bodies as indicated by the symbols. The data indicate that the best maneuvering orientation was always with the flat side down and maneuvering efficiency consistently increased with planform area at the conditions shown [8].

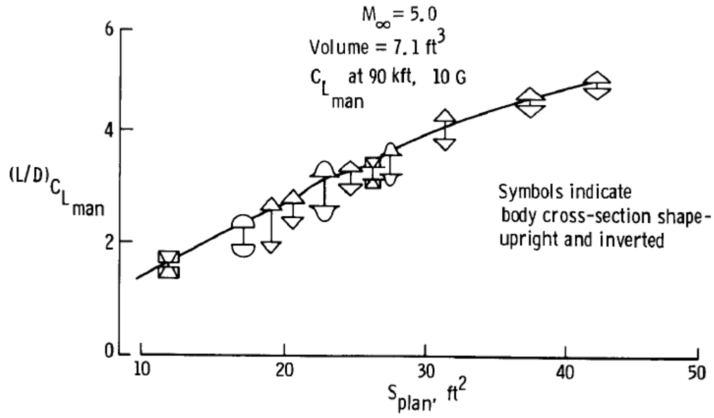


Figure 1.23 Shape, orientation, and planform area effects on missile maneuver efficiency [8]

The aerodynamic cruise and maneuvering advantages of monoplanar missile shapes are available only if adequate stability and control are maintained for the bank-to-turn guidance mode. A proper balance is desirable between the longitudinal and lateral-directional stability and control. In many cases, the same aerodynamic surfaces must be used to provide all of these functions. It is desirable to have a high degree of directional stability coupled with good pitch control up to high angles of attack. The sensitivity of these characteristics to configuration shape is illustrated in Figure 1.24. The monoplanar missile with elliptic cross section has a good balance of pitch stability and control and directional stability at high lift. The configuration with a circular cross section and the same volume and span has reduced directional stability and less pitch control. The improved directional stability effects or body cross-sectional shapes have previously been discussed. These effects can provide significant improvements in monoplanar missile configurations.

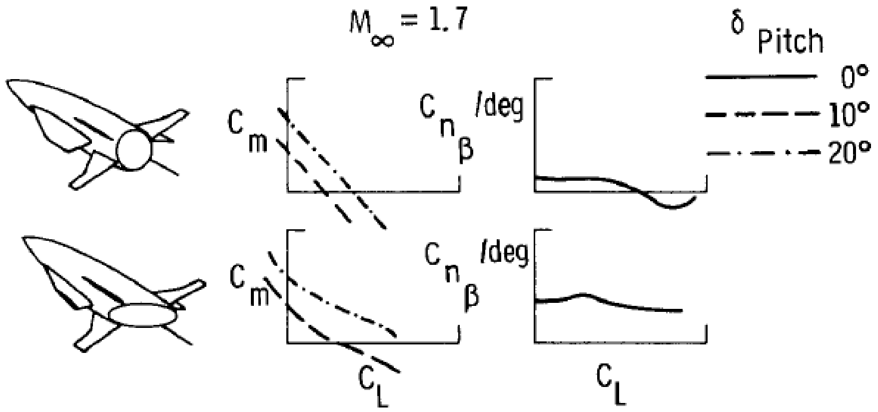


Figure 1.24 Stability characteristics of monoplanar missiles with circular and elliptic cross sections [8]

The inherent low-profile advantages or a monoplanar missile can be enhanced by providing a low-profile body shape and low-profile fins. A general cruciform aft-fin configuration can be altered to provide a low-profile configuration. Some results of a study by Blair indicate improved longitudinal performance (increased lift-curve slope) and a significant decrease in the directional stability as the side profile decreases (Figure 1.24). As the fin profile is changed by changing the hinge-line angle and the body cross-section geometry departs from circular, fin unporting problems can become quite severe [8].

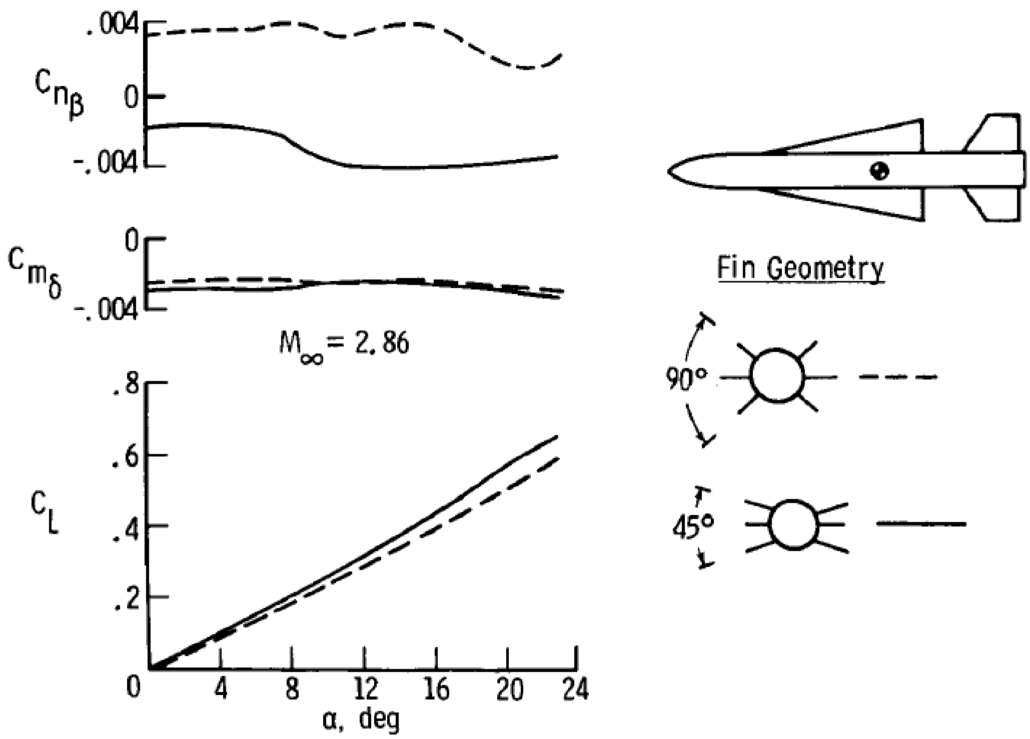


Figure 1.25 Effect of tail-fin profile on monoplanar missile performance [8]

It has been postulated that fin unporting, even for conventional shapes, can cause nonlinear variations of hinge moments with angle of deflection and angle of attack. Lamb and Trescot have made a study to evaluate fin unporting effects by altering the body shape to provide flat areas at the fin root. A comparison of the fin pressure loadings for circular body cross section (unported case) with the flat side body did not show any significant effect of unporting at fin deflections up to 6 degrees. It seems reasonable to expect unporting effects to be not only dependent on gap geometry (body radius, hinge-line location, etc.) but on local boundary- layer height at the gap. A detailed data base and analysis of the unporting effects of fins does not exist at present [23].

Finally, determining the initial configuration of a missile is very difficult for designers in preliminary design stage because there are lots of performance criteria that conflict with the others. In a family of missiles with circular and non-circular cross-sections, because of the aerodynamics, survivability, storage and carriage purposes, especially in tactical applications, there is certain need for a multi-disciplinary study. To focus on this problem, alternative designs given in the literature were analyzed in this section. As spotted in the literature especially complex configuration missiles (square, diamond, triangle, space-shuttle-like or UAV-like missiles) are of interest in optimization studies because of having aerodynamic characteristics which are extremely sensitive to orientation and need of extensive experimental studies to define aerodynamics. Also, the separation effects associated with the corners of missile cross sections result in undesirable aerodynamic stability characteristics that are difficult to predict. Thus, in this multi-disciplinary study based on circular and elliptic body shapes, objectives are aerodynamically effectiveness and survivability performance by the constraints of launch planform, internal volume and weight whose details will be given in next chapters.

1.3.3 Flight Performance and Radar Cross Section

Flight performance and trajectory optimization problem of a generic missile are investigated by Utalay in 2000. The biobjective of optimization study were the maximum range and minimum weight. Weight and flight range objectives are evaluated with respect to a given mission profile, launch and impact conditions. In addition, minimum mass and maximum trajectory problem which is constrained by impact conditions is expended by adding a Hide-Seek capability optimization. In their optimization and trajectory problem, Utalay also have control parameters and missile engine design parameters like thrust and burnout time for a solid fuel rocket engine [24].

Also, Ortaç in 2002, studied on an external configuration problem of an unguided missile with respect to maximum range and maximum warhead effectiveness. These investigations reached the advances of the methodology to achieve an optimum external configuration of an unguided missile that satisfies the defined mission requirements. The objectives of the optimization case were maximum range, minimum dispersion and maximum warhead effectiveness. The range and dispersion functions were realized with the aid of six-degree-of freedom simulations and Monte Carlo analysis depending on the external configuration parameters whereas the warhead effectiveness function was obtained by analytical means. Finally, Conjugate Gradient, Quasi Newton and Genetic Algorithm techniques for the optimization alternatives were tried and the results of these alternatives were compared with each other. As a consequence of this effort it was concluded that Genetic Algorithm (GA) has superior performance compared with gradient based methods in terms of accuracy and sensivity [25].

Another external configuration optimization problem was studied by Tanıl in 2009. The study meant to develop a software platform in MATLAB environment which gets user input by its graphical user interface and using these input parameters optimizes the external configuration of missiles. The flight requirements for the optimal design were made to be input by the designer via a graphical user interface as stated. Tanıl, in his study used three-degree-of freedom simulation algorithm, and genetic algorithm for the optimization. Air-to-air, air-to-ground and surface-to-surface missiles are included in this optimization study. By this way, it gave the opportunity of finding the optimal external geometry among a wide variety of alternatives in much shorter time intervals which satisfies the pre-defined flight mission. It consists of a graphical user interface helping the user to define the mission requirements and some basic external geometry parameters like nose type, tail configuration and engine type. The aerodynamics of each geometry alternative was evaluated by using USAF Missile DATCOM aerodynamic data prediction tool. The main cycle of the work is illustrated in Figure 1.26.

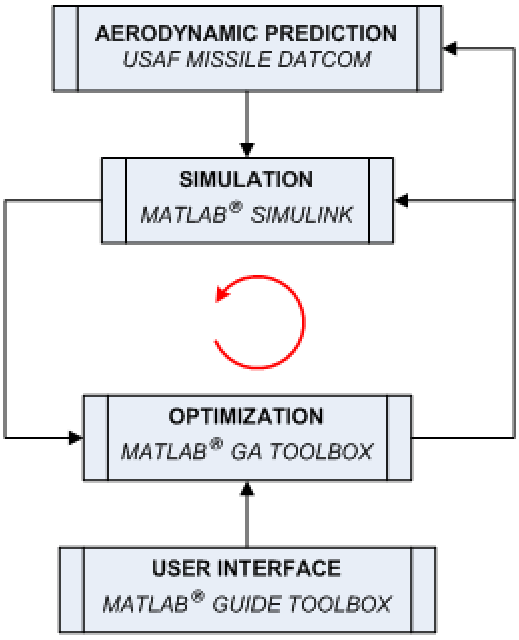


Figure 1.26 Conceptual Design Tool Flowchart [26]

Radar cross section investigations have been widely studied in the literature. However, Professor David C. Jenn and Commander Elmo E. Garrido Jr. devoloped software in 2004 called POFACETS which have positive test results and proved analyze accuracy. The POFACETS program, previously developed at the Naval Postgraduate School (NPS) as thesis work, uses the Physical Optics method to predict the RCS of complex targets, which are modeled with the use of triangular facets. The code was implemented in MATLAB and utilizes the Physical Optics (PO) approximation technique for the RCS calculation. The Physical Optics method is used to calculate the surface currents on each facet and the scattered field from all facets of a model is vector summed to produce the RCS value for given angles of incidence and observation. This technique is not overly computationally demanding and provides relatively accurate results for most large target models, while requiring minimal amounts of run–time. The initial RCS prediction code was developed by Professor David C. Jenn. Commander Elmo J. Garrido Jr. upgraded the code by adding Graphical User Interface (GUI) capabilities. The end–product is the POFACETS program, whose current version is 2.3. Flow chart of code is illustrated in Figure 1.27 [27].

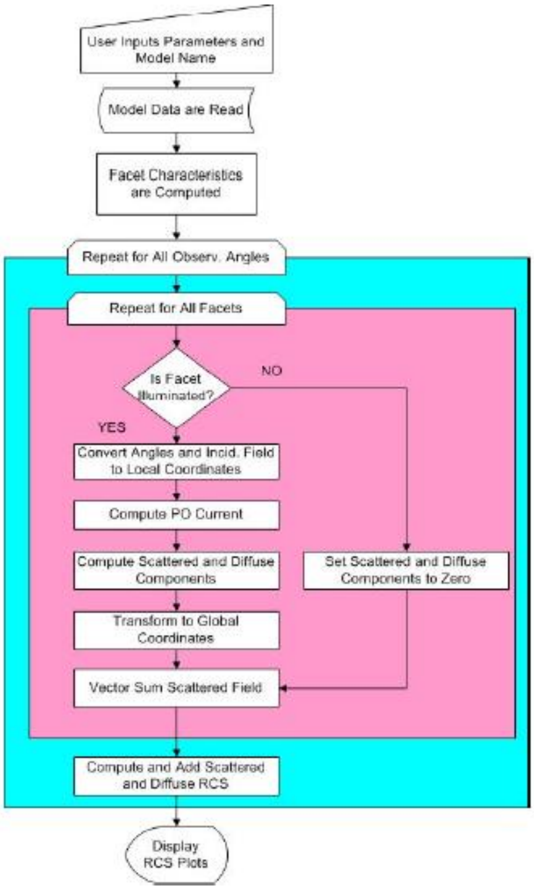


Figure 1.27 Flow chart for the RCS calculation of a collection of facets

1.4 Objective of Thesis

Although, there are lots of studies on missiles to define and compare the aerodynamic characteristics between circular and the other cross-sectional missiles, there is need of a far-reaching study concerning about not only aerodynamic properties but also survivability performances with in relation to launch planform and internal volume efficiency constraints. Thus, external configuration problem needs a multi-disciplinary optimization study. Objectives are selected as radar cross section and flight performance outputs such as flight range, stability, and control effectiveness. Before starting the optimizations study, it is necessary to define missile classifications which tend to be optimized. In this study, air-to-surface type missile was selected as the main class. These types of missiles have extended range than air-to-air and surface-to-air missiles, thus survivability of long flight time become more important issue. The mission requirements enforced designers to get maximum range with minimum radar cross section value while these two objectives are conflicting with each other especially in air-to-surface missiles.

As mentioned in the literature especially complex configuration missiles (square, diamond, triangle, space-shuttle-like or UAV-like missiles) are of interest in optimization studies because of having aerodynamic characteristics which are extremely sensitive to orientation and need of extensive experimental studies to define aerodynamics, and also, the separation effects associated with the corners of missile cross sections result in undesirable aerodynamic stability characteristics that are difficult to predict. Thus, in this multi-disciplinary study for conceptual design phase as cross section alternatives, circular and elliptic body shapes are selected.

To conclude, the aim of this thesis is multi disciplinary design and optimization of an air-to-surface turbojet powered missile to find pareto optimal solutions of external geometry configurations with circular and elliptical cross sectional shapes by the constrains of stability, control, weight and launch platform with the objectives of maximum flight range and minimum radar cross section area.

1.5 Scope of Thesis

A background introduction to the thesis topic is given in Chapter 1, including the objectives of the study with a survey of literature. The performance predictions of missile systems and importance of missile cross-sectional shape are stated. In addition, the methods and assumptions as well as the software platforms to be used in the thesis are explained in that section.

Chapter 2 presents the definition of the performance model and equations of the missiles which are aerodynamics, electromagnetic, atmosphere, and gravity are integrated and they handle the analyses in order to obtain missile performance data.

In Chapter 3, the optimization method/model and DOE model which is used in this study is mainly addressed. The external geometry optimization problem is defined by giving equations for the cost and constraints. The details of chosen genetic algorithm are also given.

Chapter 4 is a case study chapter in which a case study is employed by using mentioned methodology. Analyze inputs and outputs are defined in this section and model creations and simulation specifications are also given in this chapter.

Chapter 5 is the final chapter of the thesis in which a summary of the study is presented. The conclusion of the study is stated by explaining the beneficial sides of defining missile external configuration in preliminary design phase. And results of Chapter 4 are evaluated by charts and graphs with recommendations for future studies.

CHAPTER 2

DESIGN METHODOLOGY

Tactical missile design is an iterative process. The most important design criteria of missile conceptual design process is satisfying the missile aerodynamic needs and relevantly flight performance requirements such as, control effectiveness, stability, mass and as an objective to establish the mission requirements, range. In modern designs, there is also one more criteria which must be also satisfied at the same time with flight performance requirements, is RCS. If the survivability specification of missile is not included at the beginning of the design process, the resulting design would not be the optimum design. Thus, modern conceptual design processes require multi-disciplinary optimization study covering electromagnetics analyses with flight performance analyses together. The design method of this thesis offers following steps for multi-disciplinary optimization of a missile system (Figure 2.1):

- First, initial design space should be generated by using appropriate Design of Experiment Algorithm.

- All of the designs should be aerodynamically analyzed one by one by using USAF Missile DATCOM tool.

- Then, using these obtained aerodynamic coefficients; flight performance analyses should be carried out and by the result of these analyses missile control effectives, stability, mass and range values would have been calculated.

- After that, availability of model should be checked by constrains of control, stability and mass, and also for the available models range value stored as an objective value to evaluate it into optimization algorithm.

- Then by using defined geometrical parameters for the model, Computer Aided Model of missile should be generated by using CAD tool to use physical optic method for RCS analyses.

- And, RCS analyses should be run by using modified POFACETS RCS code.

- Finally, obtained objectives, RCS and range values of all initial design, should be evaluated and new design points should be generated by the optimization algorithm.

As stated in Chapter 1, the aim of this study is aerodynamically and electromagnetically optimization of a tactical missile. In early design phases, RCS requirements should be taken into account of design process.

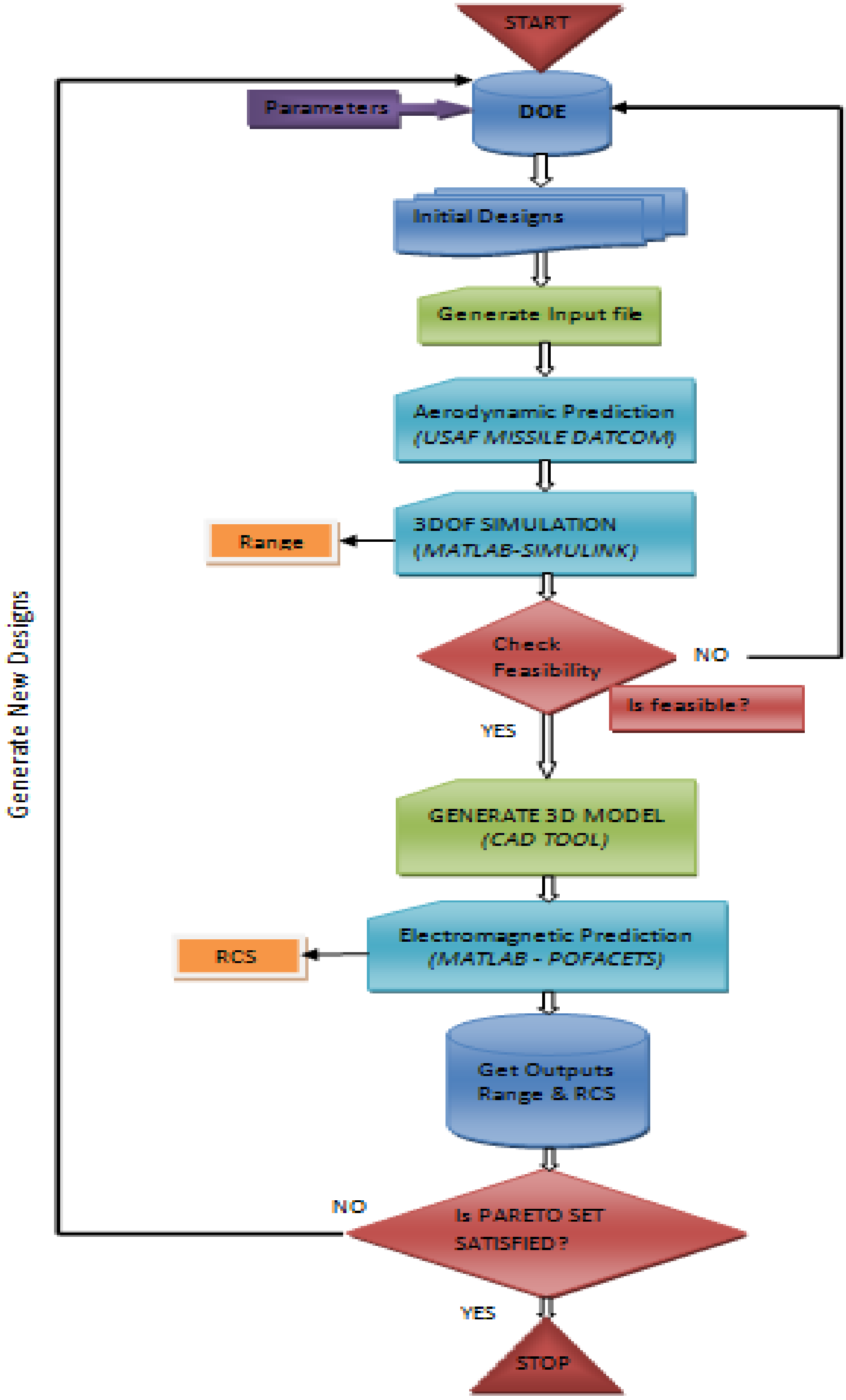


Figure 2.1 Conceptual Design Optimization Workflow

2.1 Aerodynamics Calculations

In order to calculate aerodynamic coefficients and forces acting on the missile body, accurate aerodynamic predictions is highly important. These predictions are the main step of the conceptual design process and acquired by the use of USAF Missile DATCOM software. USAF Missile DATCOM let designers make semi-empirical aerodynamic predictions and by the way with aerodynamic data base of the design space could be generated in short analyze periods. DATCOM is a corroborated code including real data and test results, thus and because of short analyze time requirement, this software commonly used in conceptual design phase of missile design process [26].

Missile DATCOM uses user defined input set as Mach vector, angle of attack vector and external geometry parameters. To calculate all unique designs in design space selected by the algorithm, unique input vector is generated and aerodynamic coefficients are calculated. The tool employ text based input and output files to define the model as well as to get initial conditions and similarly to give the results of calculations into named text based output files (Table 2.1).

Table 2.1 DATCOM input/output files

Unit	Name	Usage
2	for002.dat	Namelists for the input "case" are read from unit 8 and written to unit 2 by Subroutine READIN. The namelists for the "case" are read from unit 2.
3	for003.dat	Plot file of aerodynamic data, written at user request (using PLOT card) to unit 3 by Subroutines PLOT3, PLTTRM, or PLTUT9.
4	for004.dat	Common block data, written at user request (using WRITE card) to unit 4 by Subroutine SAVEF.
5	for005.dat	User input file, read from unit 5 by Subroutine CONERR.
6	for006.dat	Program output file, written to unit 6.
7	for007.dat	The FORMAT and WRITE control cards are written to unit 7 by Subroutine CONTRL and read by Subroutine SAVEF
8	for008.dat	User input cards read from unit 5 are written to unit 8 by Subroutine CONERR after they have been checked for errors
9	for009.dat	Body geometry data, written at user request (using PRINT GEOM BODY card) to unit 9 by Subroutines SOSE, VANDYK, or HYPERS.
10	for010.dat	Body pressure coefficient data at angle of attack, written at user request (using PRESSURES card) to unit 10 by Subroutines SOSE, VANDYK, or HYPERS.
11	for011.dat	Fin pressure coefficient data, written at user request (using PRESSURES card) to unit 11 by Subroutine FCAWPF.
12	for012.dat	Body pressure coefficient and local Mach number at zero angle of attack, written at user request (using PRESSURES) card to unit 12 from Subroutine SOSE.

The look-up table, generated by Missile DATCOM includes aerodynamic coefficients such as C_L, $C_{D,}$ and C_m and also derivative of pitch moment coefficient with respect to angle of attack, α, $C_{m\alpha}$ with pitch moment coefficient with respect to fin deflection, delta, C_{mdelta}.

Angle of attack and Mach vector is defined with respect to mission profile, and external geometric parameters are defined with respect to system requirements and physical constraints of aircraft to which the designed missile integrated, missile structure and subsystems needs.

2.2 Flight Performance Analyses

To design a suitable missile which is effectively able to complete desired mission, flight performance analyses have to be taken into account in the preliminary design phase. To predict missile range, speed and maneuverability 3 DOF and 6 DOF simulation models have been devoloped and widely used in lots of academic and military design studies. 6 DOF models have high accuracy but need more simulation time than 3 DOF models. However, in conceptual design stage of missile design studies, low-cost simulation time is necessary because of large design spaces. Thus, 3 DOF missile trajectory simulations are widely used in order to reduce calculation time of these large design spaces in conceptual design stage.

There are a lot of 3 DOF simulation model in the literature. One of them is Brouch’s 3 DOF pitch model which consist of some basic improvements in a simple 3 DOF model. With these insertions, level of accuracy and fidelity of model are increased and relative error is decreased from 12% than 3%, while 3 DOF model is twice faster than 6 DOF one.

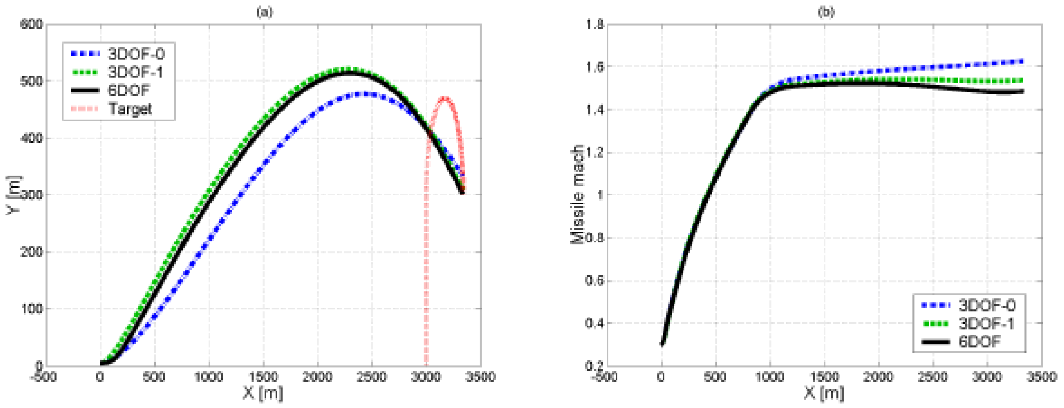


Figure 2.2 (a) Missile trajectory; (b) Missile Mach number as a function of the missile range [20]

So, in the conceptual design phase, to determine behavior of large design space with low-cost design time; a three degree of freedom pitch model is thought to be suitable and a six degree of freedom model is rather unnecessary and time consuming effort for the conceptual design approach. At conceptual design stage, desired design is baseline missile geometry rather than a detailed one. More detailed design requires more design parameters on the missile configuration which means much time to spend for calculating the effects of various design parameters on the missile configuration.

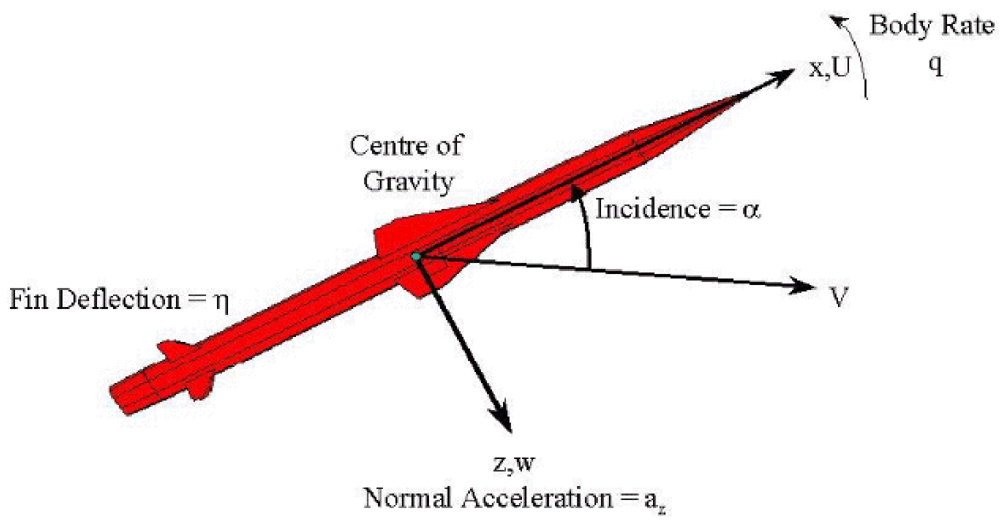


Figure 2.3 The 3DOF Pitch Model

The designed 3 DOF model is employed with inputs from aircraft flight and drop conditions, given mission profile requirements and missile external geometry parameters as shown in Figure 2.4.

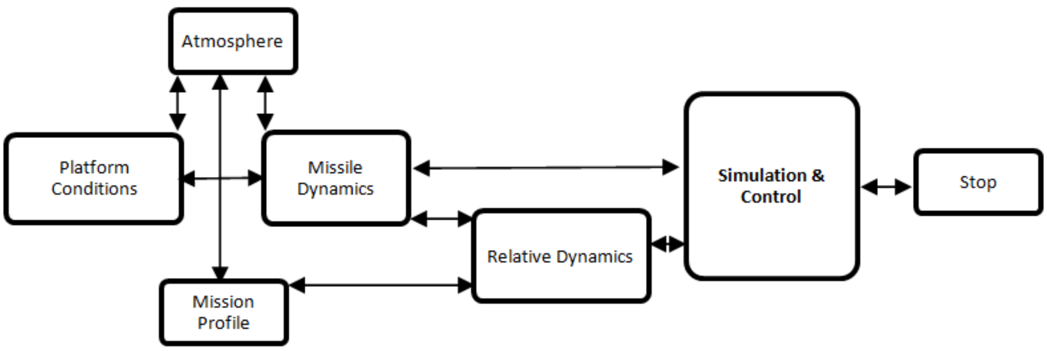


Figure 2.4 Three DOF Model Workflow

The 3 DOF pitch model includes two translational and one rotational motion. The translational motions are the axial (range) and vertical (altitude) motions while the rotational motion is angular motion about the lateral axis (pitch) as shown above in Figure 2.3. Missile dynamic model includes some sub-models as Equations of Motions Model, Aerodynamic Database which generated using Missile DATCOM as specified before; air density and aerodynamic forces and moments are calculated in this step, 1976 COESA atmosphere assumption, Propulsion inputs, Control Model with mission requirements by means of this model desired angle of attack are calculated and the last one is Gravity Model (Figure 2.5).

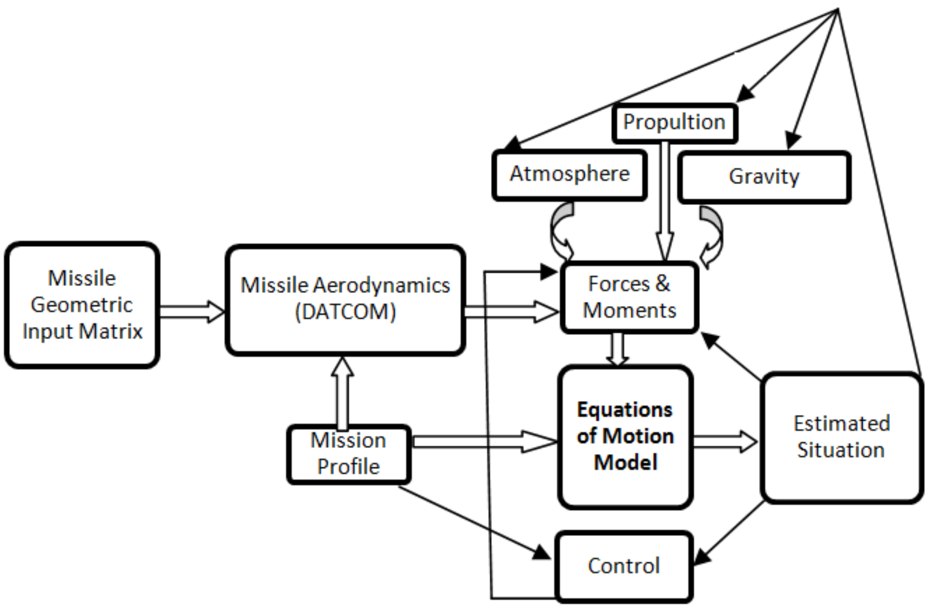


Figure 2.5 Missile Dynamic Model

In this multi-disciplinary study, because survivability is much more important issue for air-to-surface missile than surface-to-air and air-to-air missiles, air-to-surface missile type is chosen as missile type.

2.2.1 Equation of Motion

As stated above, only the vertical planar motion of the missile against gravity is considered. The equations of motion are defined in missile body axis system; the frame which is fixed to the missile and moves with it, having its origin at the center of gravity (CG) as illustrated in Figure 2.6.

The instantaneous position of the missile is defined relative to the earth fixed frame whose coordinate axes are remain fixed with respect to the earth and its origin is located at the mass center of the earth. It is denoted with the abbreviation "*b*" in Figure 2.6.

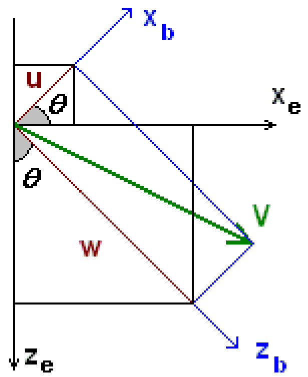


Figure 2.6 Body and Earth Axes

The related dynamic equations of motion are given as below. The applied forces are assumed to act at the center of gravity of the body.

$$\dot{u} = \frac{F_X}{m} - \frac{\dot{m} \cdot u}{m} - q \cdot u \tag{2.1}$$

$$\dot{w} = \frac{F_Z}{m} - \frac{\dot{m} \cdot w}{m} + q \cdot u \tag{2.2}$$

whereas *u* and *w* are the forward and the downward velocities of the missile body axis, respectively.

$$\dot{q} = \frac{M - \dot{I_{yy}} \cdot q}{I_{yy}} \tag{2.3}$$

$$\dot{\theta} = q \tag{2.4}$$

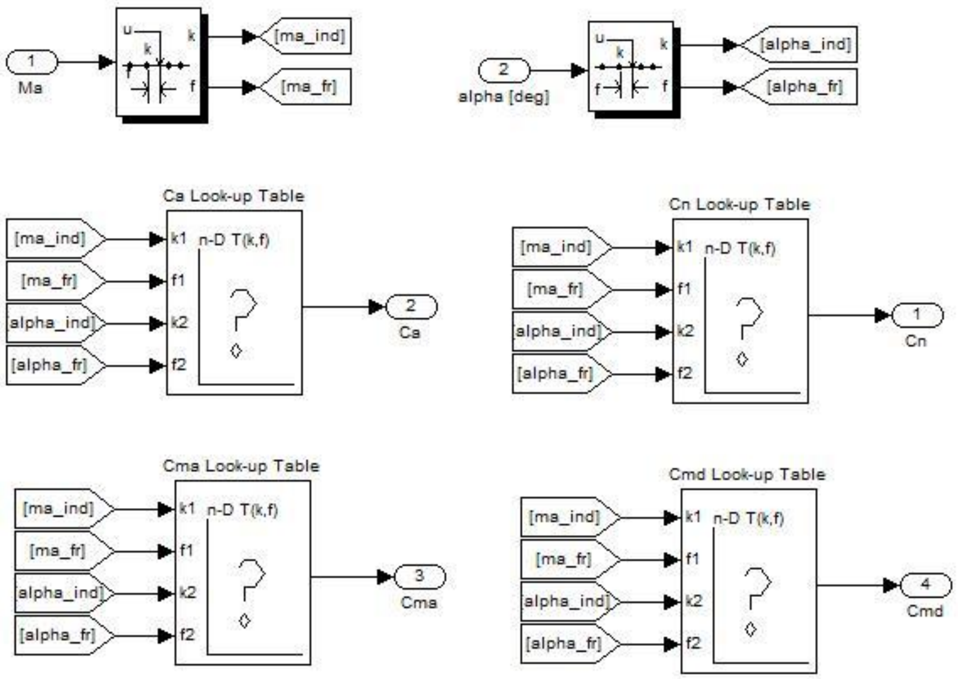
Hence the angular orientation of the missile in pitch plane is indicated as the angle θ.

To evaluate the position of the missile with respect to the earth fixed frame, the velocities defined in body fixed frame should be transformed into the earth fixed frame via the transformation angle θ owing to the fact that only a single angle is needed to specify a rotation in two dimensions that is the angle of rotation. Finally the desired positions are found as a result of the integration of velocities transformed into the earth fixed frame. The matrix equation can be given as,

$$\begin{bmatrix} \dot{x_e} \\ \dot{z_e} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u \\ w \end{bmatrix} \tag{2.5}$$

2.2.2 Aerodynamics

The aerodynamic forces and moments acting on the missile are generated in this submodel. For a three degree of freedom model, the required aerodynamic coefficients are axial force coefficient C_A, normal force coefficient C_N and pitch moment coefficient C_m. Additionally, the longitudinal stability term $C_{m\alpha}$ is also evaluated at the same flight conditions.



“

Figure 2.7 Aerodynamic Look-Up Tables

Since the lateral effects are not considered, the sideslip angle, β, is always set to 0° and the force and moment coefficients are evaluated at this value. Considering the flight conditions frequently encountered for a generic air-to-ground missile, the domain of the angle of attack, Mach number and elevator deflection angles, at which the aerodynamic data would be generated, are set as follows,

Angle of Attack = [-10 , -7 , -4 , -2, 0 , 2 , 4 , 6 , 8 ,10]

Mach = [0.1, 0.3 , 0.5 , 0.6 , 0.7 , 0.8 , 0.9 , 1.0 , 1.1 , 1.2]

Elevator Deflection Angle = [0, 5]

The force coefficients to be used in the flight simulation loop are lift and drag coefficient, however. Lift is the aerodynamic force perpendicular to the total velocity vector of the missile and drag is the one in the direction of the total velocity vector defined in the stability axis system of the missile which is aligned with the velocity vector in a reference condition of steady symmetric flight. Hence the lift and drag coefficients are able to be calculated using normal and axial force coefficients via a transformation from the body axis to the stability axis utilizing the angle of attack. All the axes systems, angles and forces are illustrated as in Figure 2.8. T stands for the thrust force and W for the gravitational force. On the other hand α, γ and θ angles are angle of attack, flight path angle and pitch angle respectively. [x_E, z_E] is the earth fixed axis, [x_s, z_s] defines the stability axis and finally [x_b, z_b] stands for the body fixed axis.

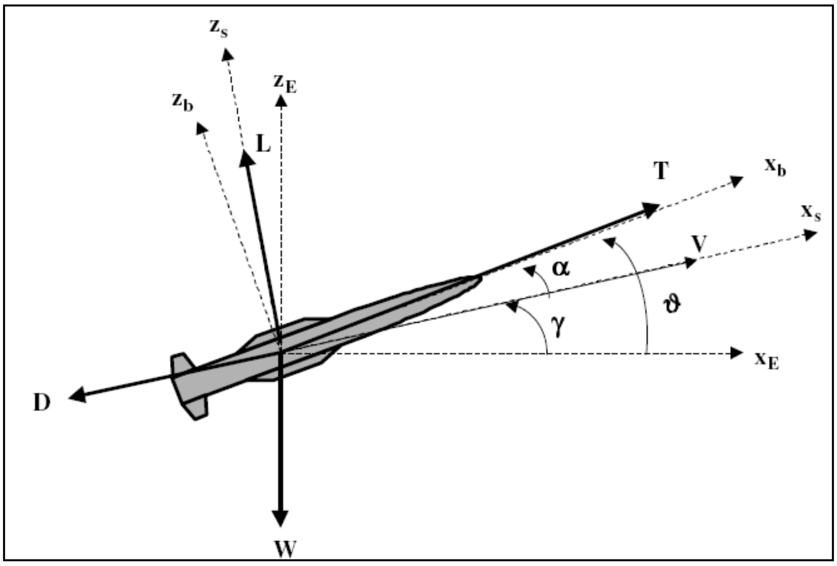


Figure 2.8 Forces and Angles on Body, Stability and Earth Axes

The equations for the lift and drag force coefficients are obtained from the normal and axial force confidents with the equations shown below.

$$C_L = C_N \cos\alpha - C_A \sin\alpha \tag{2.6}$$

$$C_D = C_A \cos\alpha + C_N \sin\alpha \tag{2.7}$$

The lift and drag forces and the pitching moment are then calculated by using the model below.

$$L = \frac{1}{2}\rho V^2 S C_L \tag{2.8}$$

$$D = \frac{1}{2}\rho V^2 S C_D \tag{2.9}$$

$$M = \frac{1}{2}\rho V^2 S d C_M \tag{2.10}$$

where ρ is the air density, S is the reference area which is the cross sectional area of the missile and d is the reference length, which is the diameter of the missile.

In addition to these coefficients, the elevator deflection, δ_e dependency of the pitch moment coefficient should be calculated for the control effectiveness consideration. To do this, the slope of the change of pitch moment coefficient with respect to the elevator deflection angle is calculated as,

$$Cm_{\delta e} = \frac{Cm@\,\delta_{e1} - Cm@\,\delta_{e2}}{\delta_{e1} - \delta_{e2}} \tag{2.11}$$

The aerodynamic data are evaluated at two elevator deflection angles 0˚and 5˚.

2.2.3 Atmosphere

In order to calculate the speed of sound and the air density at each altitude of the flight, the 1976 COESA lower atmosphere model available at Simulink library of MATLAB R2008b is implemented. Mathematical model of the 1976 Committee on Extension to the Standard Atmosphere which defines United States standard lower atmospheric values for absolute temperature, pressure, density, and speed of sound for the input geopotential altitude (COESA) is integrated in the COESA Atmosphere Model block [28]. Mentioned block is illustrated in Figure 2.9.

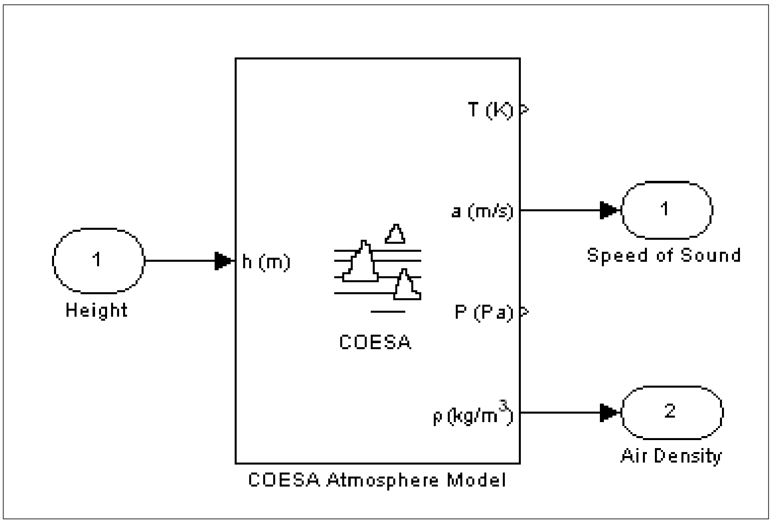


Figure 2.9 1976 COESA Atmosphere Model

2.2.4 Control

The optimal missile geometry is tending to be attained to acquire a pre-defined mission profile. Through the concept of this thesis, it is assumed to be composed of a glide, descent, cruise, climb and descent phase or a sequence of glide, descent, cruise and dive phases. The control model consists of simple proportional control models to achieve the necessary angle of attack commands and the thrust force at each flight phase and maintains the cruise altitude value given by the user at the cruise flight phase.

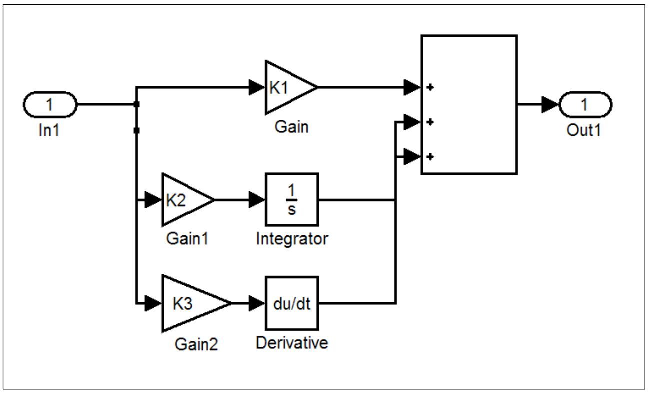


Figure 2.10 PID Control Model

2.2.5 Gravity

Because of including the effect of the altitude on the gravitational acceleration 1984 World Geodetic System (WGS84) model again available at Simulink library of MATLAB R2008b is used which implements the mathematical representation of the geocentric equipotential ellipsoid of the World Geodetic System (WGS84). The block output is the Earth's gravity at a specific location [29].

2.3 Parametric CAD Model

Missile 3D solid model is created to be used in electromagnetic analyses. Because finite element method is used in these analyses, missile 3D model is needed to be parametrically drawn. So, in order to create missile solid model, CAD tools in which a script automatically employs the tool are used to generate models. An automatic drawing code is written in this study. The models exported in stl data format which is made by triangle facets. The code mainly works by using the algorithm in Figure 2.11.

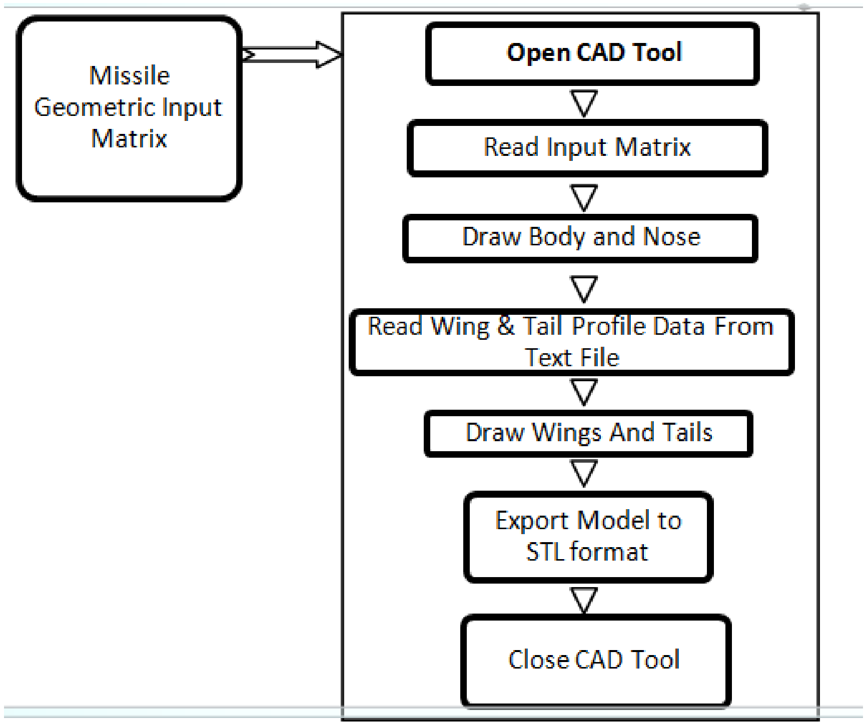


Figure 2.11 CAD Model Automatically Drawing Steps

First, geometric design parameters generated by design of experiments or optimization algorithm. Then code reads the geometric data from a text based input file and using these data, nose and body of generic missile is drawn. After that, wing (NACA) and tail profile data are taken from another text input file. They are also automatically drawn into model. Finally full scale model are exported to stl data format for the radar cross section estimation code. Some of the sample models are given below.

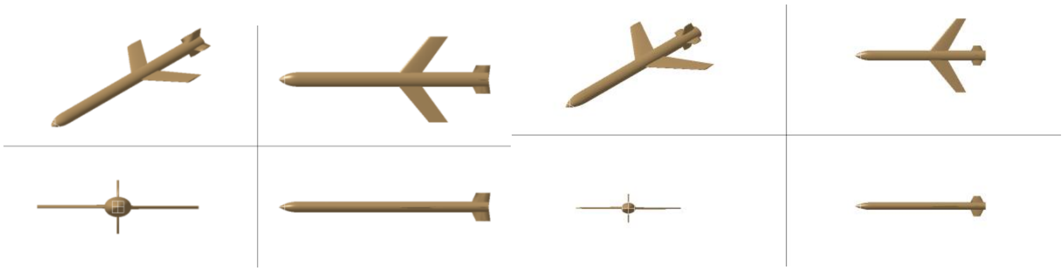


Figure 2.12 Sample Elliptic and Circular Parametric CAD Models of Missile Geometry

2.4 Electromagnetic Predictions

RCS is a measure scattering received at a receiver from an object. RCS is defined in IEEE [30] as ‘For a given scattering object, upon which a plane wave is incident, that portion of the scattering cross section corresponding to a specified polarization component of the scattered wave’. The RCS can be defined in terms of incident and scattered field intensities as

$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{\left|\vec{E}_s\right|^2}{\left|\vec{E}_i\right|^2} \tag{2.12}$$

where E_s and E_i are the scattered and incident field intensities, respectively. RCS analysis and control are already studied and explained in several books in literature [30] [31] [32]. In this thesis, only basic explanations are given to understand the significance of the RCS.

The radar equation in a simple form can be expressed as

$$P_r = \left(\frac{P_t G_t}{4\pi R^2}\right)\left(\frac{\sigma}{4\pi R^2}\right)\left(\frac{G_r \lambda^2}{4\pi}\right) \tag{2.13}$$

where P_r is the power received by the radar, P_t is the output power of the transmitter, G_t and G_r are the gains of transmitter and receiver antenna, respectively, σ denotes the radar cross section of the target, λ represents the wavelength of the radar’s frequency, and R is the range between the radar and target. The first term in the parenthesis at the right side of the equation is the power density at the target (W/m^2). The product of the first and second terms in the parenthesis represents the power density at the radar receiver. Finally, the third term is the power captured by the receiving antenna. The RCS is called as monostatic if the transmitter and the receiver are collocated.

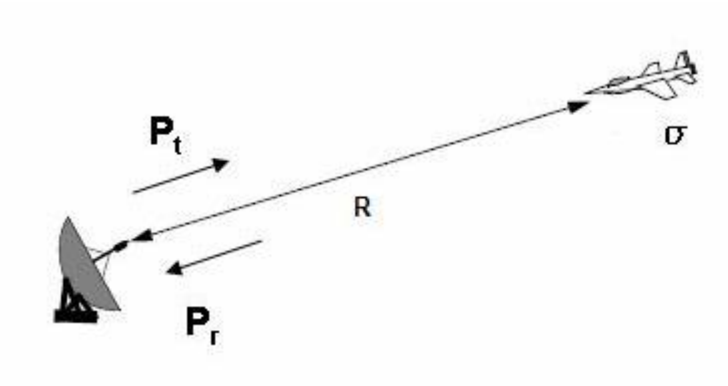


Figure 2.13 Generic Radar-Target Configuration (Monostatic)

For the monostatic radar configuration which is shown in Figure 2.13

$$G = G_t = G_r \tag{2.14}$$

Then, Equation 2.12 can be rewritten as

$$P_r = \frac{P_t G^2 \sigma \lambda^2}{(4\pi)^3 R^4} \tag{2.15}$$

The range of radar is defined as the distance beyond which the target cannot be detected. Hence,

$$R_{radar} = \left(\frac{P_t G^2 \sigma \lambda^2}{(4\pi)^3 S_{\min}} \right)^{1/4} \tag{2.16}$$

where $S_{\min}$ is the threshold value for the signal that can be detected by the receiver. Equation 2.15 dictates that detection range of radar is proportional to $\sigma^{1/4}$ Free detection range decreases 50 % if the RCS of the target is reduced by a factor of 16 (2^4). Table 2.2 illustrates the effect of RCS reduction on the target detection range.

Table 2.2 Effect of RCS reduction on the detection range [27]

RCS Reduction, %	RCS Reduction, dB	Detection Range
0	0	100 (arbitrary)
90	10	56
99	20	32
99.9	30	18
99.99	40	10

Table 2.2 illustrates the effect of RCS on the detection range for a target flying at an altitude of 10000 ft [27]. As the transmitted power of the radar increases

detection range gets larger. Furthermore, reduction in RCS reduces detection range, beyond which no threat is encountered significantly.

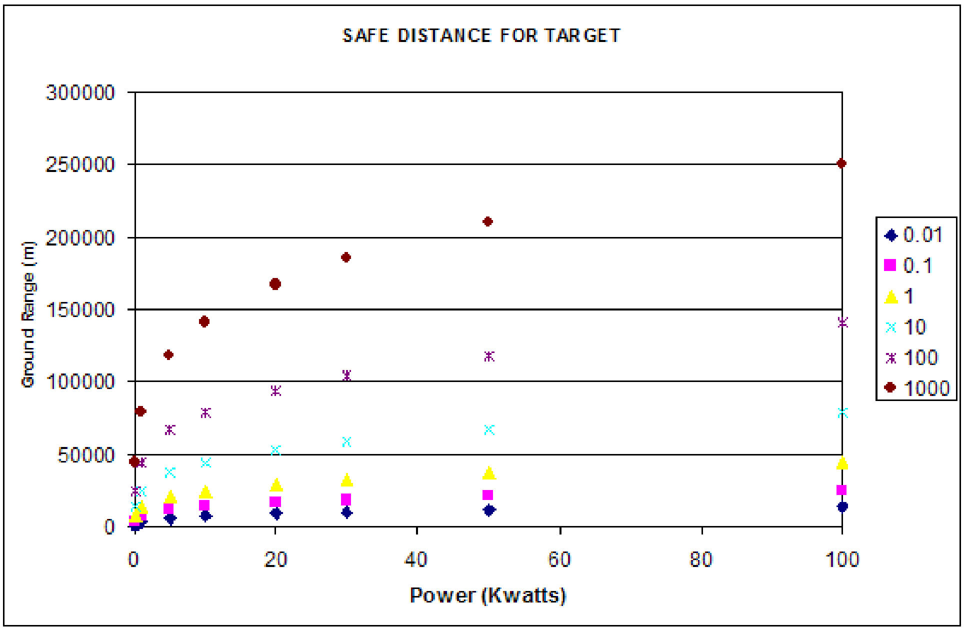


Figure 2.14 Effect of RCS on the detection range

The RCS is usually expressed in decibels relative to a square meter (dBsm):

$$\sigma[dBsm] = 10\log(\sigma[m^2]) \tag{2.17}$$

The RCS of a target is dependent on several parameters listed as:

- the geometry of the target,

- the material (s) of the target,
- the frequency of incident,
- the polarizations antennas,
- the positions of antennas relative to the target.

There are three distinct frequency regions in which the RCS of the target is different. These regions are expressed in terms of the length, L and the incident wavelength, λ:

1. Low Frequency-Rayleigh Region $\left(\frac{2\pi}{\lambda}L << 1\right)$: In this region, variations in the shape of the target do not significantly affect the scattering characteristics of the target. Generally, σ varies as $1/\lambda^4$.
2. Mie-Resonance Region $\left(\frac{2\pi}{\lambda}L \approx 1\right)$: Small changes in phase and or frequency create significant variations in σ.
3. High Frequency-Optical Region $\left(\frac{2\pi}{\lambda}L >> 1\right)$: The scattered field is highly dependent on the orientation of the target with respect to the radar while σ versus characteristic frequency is smooth.

RCS of a sphere within radius is given in Figure 2.15, where $\beta = 2\pi/\lambda$. Three distinct regions can be designated as $\beta a < 0.5$ (Rayleigh), $0.5 < \beta a < 10$ (Resonance), $\beta a > 10$ (Optical). One can see that RCS is constant and equal to πa^2.

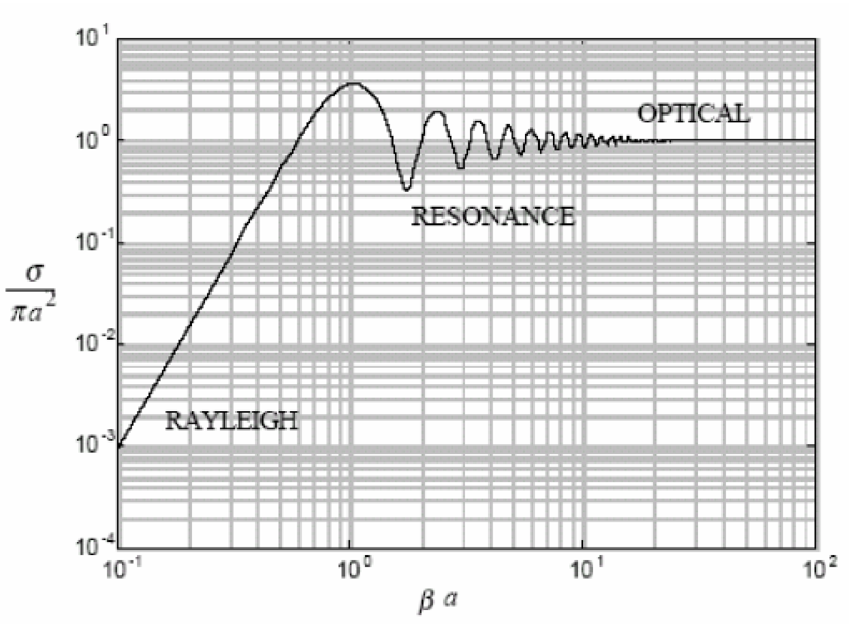


Figure 2.15 RCS of Sphere [31]

The most common RCS prediction methods are the Finite Difference Method, the Method of Moments, Microwave Optics (the Geometrical Optics method and the Geometrical Theory of Diffraction method) and the Physical Optics. In this study, the Physical Optics method is utilized for the prediction of RCS. The Physical Optics method approximates the surface currents induced on the surface by setting them to be simply proportional to incident magnetic field intensity on the illuminated side of the body using geometrical optics. On the shadowed portion, the current is set to zero. The currents are used to compute the radiation integrals. The method provides good results for electrically large targets (at least 10 wavelengths in size). The method does not include surface waves, multiple reflections and edge diffraction [33]. RCS of targets can be predicted for various frequency and orientations relative to radar with convenient computation times.

Missile as a target is approximated by a model consisting of triangular facets which is generated by 3D model generation code as stated in Section 2.3. Model of the target is established by means of Solid Modeling Program and exported to RCS prediction software Stereo Lithographic (STL) format. The scattered field for the target is computed by vector-summing of scattered fields of individual facets. Furthermore, illumination condition (illuminated or shadowed) and resistivity information for each facet is supplied. RCS prediction software processes the model and the facet information to compute RCS for required frequency and orientation values. Coordinate system utilized is shown in Figure 2.16.

The Physical Optics method is very convenient tool for preliminary design phase in which designers are required to examine large number of design variables to obtain feasible configurations.

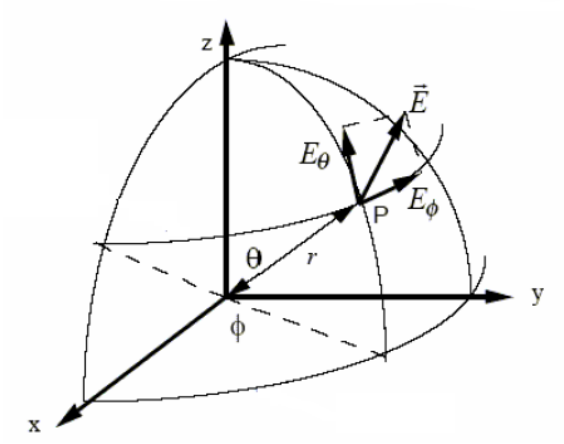


Figure 2.16 Coordinate System

CHAPTER 3

MULTI-DISCIPLINARY DESIGN OPTIMIZATION

Constraint optimization problem is solved by making use the Multi Disciplinary Genetic Algorithm. Multi Disciplinary Genetic Algorithm (MOGAII) multi-disciplinary optimization algorithm employed to get pareto optimal solutions of missile preliminary design problem. Details of the algorithm will be given in next sub headings of this chapter. The objectives of the optimization problem are defined as flight range and radar cross section of the designed missile. The design constraints are flight range, control effectiveness and total mass of missile with some physical platform integration and structural constraints whose details also will be given below. The summary of optimization workflow is given in Figure 3.1.

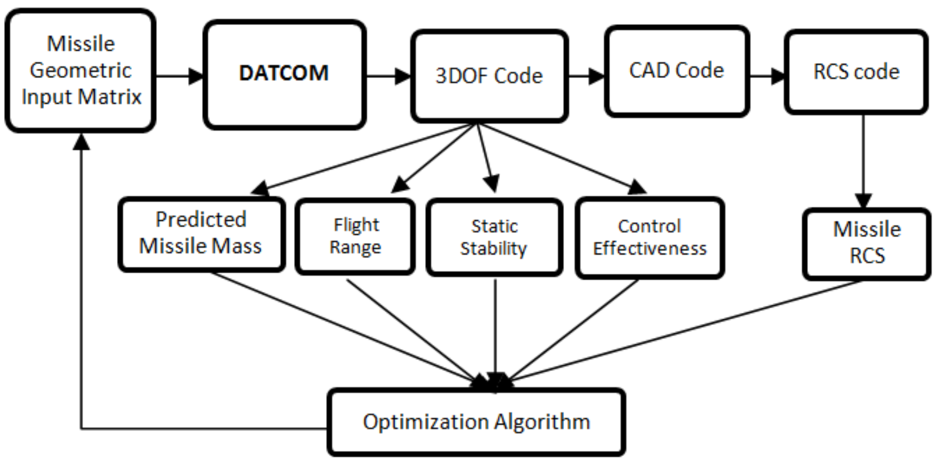


Figure 3.1 Optimization workflow

Optimization problem is formulated as

Maximize: $f_1 = FlightRang\,e$

Minimize: $f_2 = \frac{1}{4}\left([RCS]_{\theta=0} + [RCS]_{\theta=90} + [RCS]_{\theta=180} + [RCS]_{\theta=270}\right)$

Subject to: $25 \geq \text{missile body finess ratio}(\frac{\text{L}}{\text{D}}) \geq 5$ Structural Constraint

$$\frac{C_{m_\delta}}{C_{m_\alpha}} = \frac{\Delta C_m}{\Delta \delta}\frac{\Delta \alpha}{\Delta C_m} = \frac{\Delta \alpha}{\Delta \delta} > 1$$ Control Effectiveness Constraint

$\Delta C_m/\Delta\alpha < 0$ Static Stability Constraint

$$\begin{aligned} PlatformCapability &\geq TotalLenght \\ PlatformCapability &\geq WingSpan \\ PlatformCapability &\geq Diameter \end{aligned}$$ Platform integration constraint

3.1 Design Parameters

The external geometry parameters are the main drivers that affect the missile flight performance such as range, stability, weight, maneuverability and controllability. Therefore the main focus of this thesis is to find the optimum geometric parameters of the missile.

The main design steps to be followed up at the conceptual design phase of an air to ground missile are discussed in detail in the upcoming sections.

3.2 External Geometry Parameters

Missile cross section has two alternatives, elliptical body cross section and circular body cross section. Also, cross section radius and ellipticity factor are body parameters. In addition to these, as seen from Figure 3.2 missile tail and wing span, nose and body section lengths, wing and tail sweeps, wing and tail chords and thicknesses are other external geometry parameters.

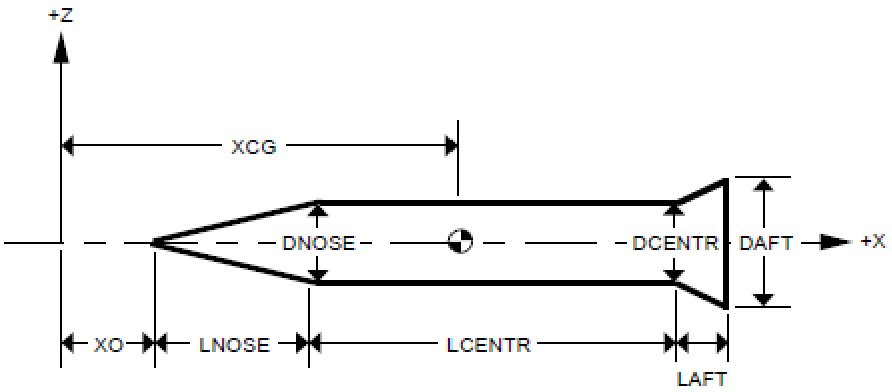


Figure 3.2 Missile Body External Geometry Parameters

3.2.1 Nose Types

The nose type is such an important parameter that it has a major effect on the drag force acting on the missile. In the scope of this work, the nose length is one of the geometric parameters to be optimized. The nose diameter is taken into account in such a way that it is equal to the body diameter at the end. The nose shape alternatives that can be modeled in Missile DATCOM are Ogive, Conical, Power, Haack and Karman. The equations and definitions of these nose types are specified as below. The variable L defines the nose length and *R* defines the nose radius at the end of the nose. The other variables are *x*, which stands for the axial distance from the tip of the nose and *y*, for the radius at any point of the nose [36]. These variables are clearly illustrated in Figure 3.3.

It is the most popular nose type used in missiles due to its ease in production and low drag profile characteristics. The nose length should be equal to or less than the ogive radius. The radius of the circle is called as the ogive radius and defined as in the equation below [37].

$$\rho = \frac{R^2 + L^2}{2R} \tag{3.1}$$

Besides, the radius at any point on the whole missile length is formulized as;

$$y = \sqrt{\rho^2 - (L_N - x)^2} + R - \rho \tag{3.2}$$

where L_N is the nose length and *x* is the point on the missile axial direction.

The power series type for nose geometry is simply defined as in the formula and the figure below in Missile DATCOM where the parameter *n* is an indicator of the nose roundedness.

$$y = R\left(\frac{x}{L_N}\right)^n \quad \text{where} \quad 0 \le n \le 1 \tag{3.3}$$

This is another nose type alternative that has a wide usage since this shape is often chosen for its ease of manufacture [38].

The other nose type alternatives Haack and Von Karman are mathematically modeled as below.

Haack,

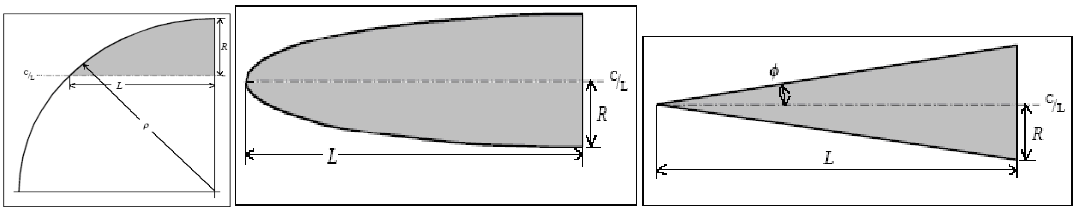
$$y = R\sqrt{\frac{1}{\pi}\left(\theta - \frac{\sin(2\theta)}{2} + \frac{1}{3}\sin\theta^{3}\right)} \tag{3.4}$$

Von Karman,

$$y = R\sqrt{\frac{1}{\pi}\left(\theta - \frac{\sin(2\theta)}{2}\right)} \tag{3.5}$$

where,

$$\theta = arc\cos\left(1 - \frac{2x}{L}\right) \tag{3.6}$$



(a) (b) (c)

Figure 3.3 (a) Ogive, (b) Power Series, (c) Conical Nose Geometry

3.2.2 Roll Orientation

Roll orientation affects the stability and control effectiveness of the missile. The symmetric roll orientation approaches are mainly plus (+) and cross(x) alternatives which are shown in Figure 3.4.

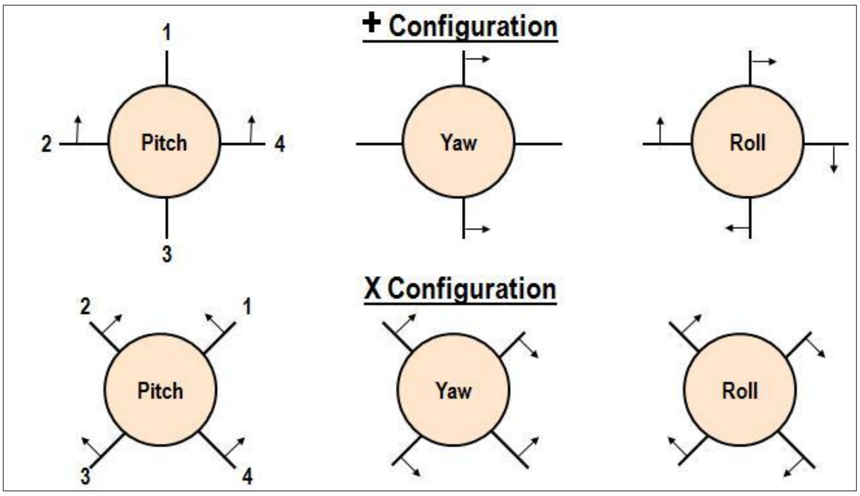


Figure 3.4 Roll Orientation Alternatives

Each has distinct advantages and disadvantages. Plus configuration has the simplest control mechanism. It usually has an advantage of lower drag. As stated formerly, only the motion in pitch axis is considered in this thesis. For pitch command, two surfaces provide normal force into the pitch direction. The positive control deflection direction for plus configuration to induce a positive rolling moment and the pitch control allocation formula are shown as below.

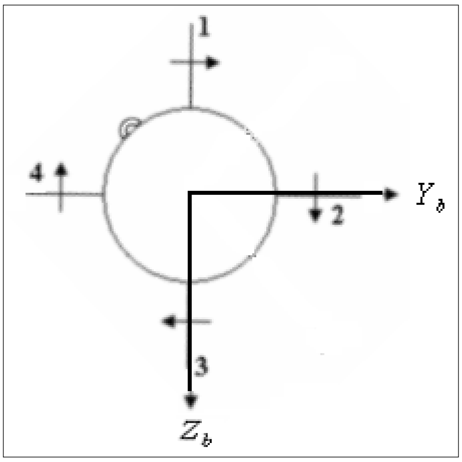


Figure 3.5 Plus Configuration Positive Control Deflection Direction (Back View)

$$\delta_e = \frac{\delta_2 - \delta_4}{2} \tag{3.7}$$

An alternative approach, the cross configuration during missile flight is somewhat more complex to control. For pitch command, all four surfaces are deflected to provide normal force without side force. The cross configuration often has advantages or better fit for launch platform compatibility and higher aerodynamic efficiency that is to attain a high lift to drag ratio [1]. The positive control deflection direction for cross configuration to induce a positive rolling moment and the pitch control allocation formula are shown in Figure 3.6.

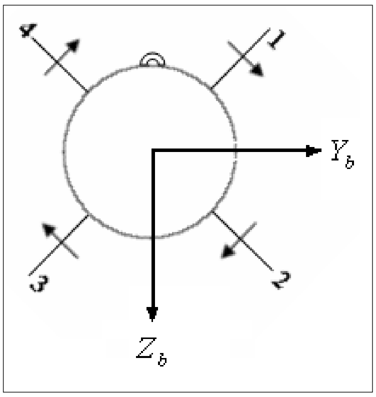


Figure 3.6 Cross Configuration Positive Control Deflection Direction (Back View)

$$\delta_e = \frac{\delta_1 + \delta_2 + \delta_3 + \delta_4}{4} \tag{3.8}$$

3.3 Design Objectives

Once the outlines for the air-to-ground missile external geometry are decided, the critical question rises up at the same time. What is the rule of thumb to judge the performance of the missile? From the point of view of the designer who tries to designate the optimal missile geometry at the very beginning of the design process, the missile is intended to reach its maximum flight range with a RCS as minimum as possible. However, while acquiring these criteria, the missile to be designed would be expected to be longitudinally stable, controllable in pitch axis and maneuverable enough to follow up the given trajectory, especially in pull-up maneuvers and in order to overcome disturbances. Hence, to converge to a design that is sensible in terms of dynamics, propulsion and weight as well as satisfying the flight performance requirements listed above is the ultimate goal at the conceptual design stage of an air-to-ground missile. In the current study, all these cirtieria are able to be evaluated by means of the simulation module of the whole process. Next, the measures of merit for the candidate missile are discussed.

3.3.1 Flight Range

The designed missile is expected to reach a flight range which is as maximized as it can. This is one of the objectives of the missile design optimization problem. For the evaluation of cruise flight performance, the Brequet range equation provides an estimate of the missile flight range during cruise flight as it is expressed in [34] as,

$$R = \left(\frac{L}{D}\right)\left(I_{sp}\right)\left(V_{AVG}\right)\ln\left(\frac{W_L}{W_L - W_F}\right) \tag{3.9}$$

The constant velocity, constant lift-to-drag ratio and constant specific impulse are the main assumptions made in the derivation of the Brequet range equation. Besides, W_L stands for the launch weight while W_F for the fuel weight.

It is followed from the Brequet range equation that it is essential to fly at maximum lift-to-drag ratio to achieve the maximum flight range for the given missile configuration. Lift–to-drag ratio, which is an indicator of the aerodynamic efficiency, depends on the angle of attack. Angle of attack could vary in flight phases except from the cruise phase. Due to the roughness in the estimation of the flight range utilizing the Brequet range equation, the range value is tried to be evaluated via three-degree-of freedom simulation.

Finally, the speed of the missile and the thrust force realized can be controlled during the flight for a turbojet powered missile. Moreover the turbojet powered missile is not desired for time-critical missions since the accuracy of the hit point of the target is the main priority. Owing to all these reasons, maximization of the cruise flight speed is not treated as an objective. Instead, cruise speed is tried to be adjusted in such a way that it is closer to the value defined by the designer.

3.3.2 Radar Cross Section

RCS prediction software processes the model and the facet information to compute RCS for required frequency and orientation values. Coordinate system utilized is shown in Figure 2.16.

The Physical Optics method is very convenient tool for preliminary design phase in which designers are required to examine large number of design variables to obtain feasible configurations.

The radar equation in a simple form can be expressed as

$$P_r = \left(\frac{P_t G_t}{4\pi R^2}\right)\left(\frac{\sigma}{4\pi R^2}\right)\left(\frac{G_r \lambda^2}{4\pi}\right) \tag{3.10}$$

3.4 Design Constraints

In the penalty function method, infeasible solutions are penalized in each generation, and the overall penalty is added to the original objective function to form the fitness function for the evolutionary algorithms.

The penalty is defined as follows:

$$\phi(\vec{x}) = \sum_{j=1}^{m} g_j(\vec{x})\delta_j(\vec{x}) \tag{3.11}$$

where $\delta_j(\vec{x})=1$ if $g_j(\vec{x})>0$ and zero otherwise.

The fitness function for objective f_i corresponding to an individual $\vec{x}$ is

$$\psi(\vec{x}) = f_i(\vec{x}) + R\phi(\vec{x}) \tag{3.12}$$

R is a penalty parameter. In this case, there are two objectives so there will be two fitness functions with the same penalty component.

3.4.1 Static Stability

Static stability in pitch is defined by the slope of the pitching moment coefficient, versus angle of attack. To ensure the static stability of the missile, the slope of the pitching moment coefficient versus angle of attack should be negative as shown in Figure 3.7 ($\Delta C_m/\Delta\alpha < 0$) Figure 3.7.

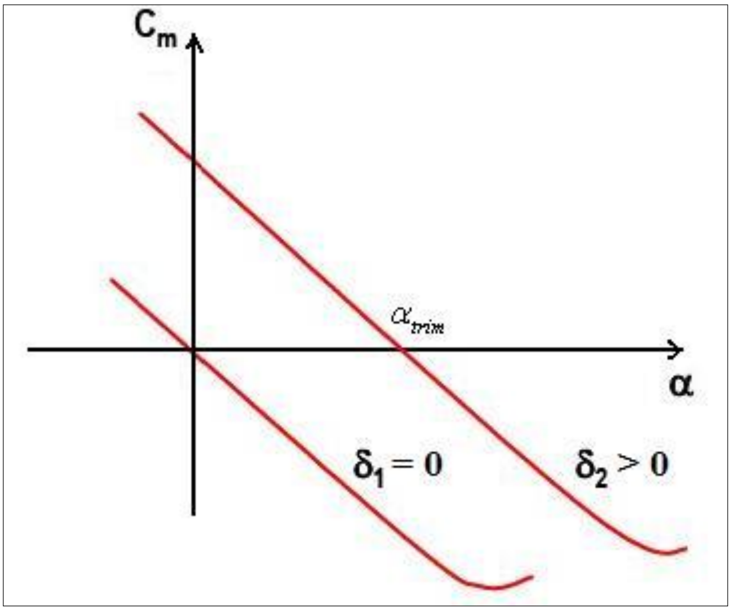


Figure 3.7 *Cm* versus α Curve

An increase in angle of attack (nose up) causes a negative incremental pitching moment (nose down), which then tends to decrease the angle of attack [35].

Tail control surfaces give the way that the missile could be restored to its trimmed flight at the desired angle of attack. These phenomena could be attained by taking the center of pressure (C_P) closer to the tail than center of gravity (*CG*) as shown Figure 3.8.

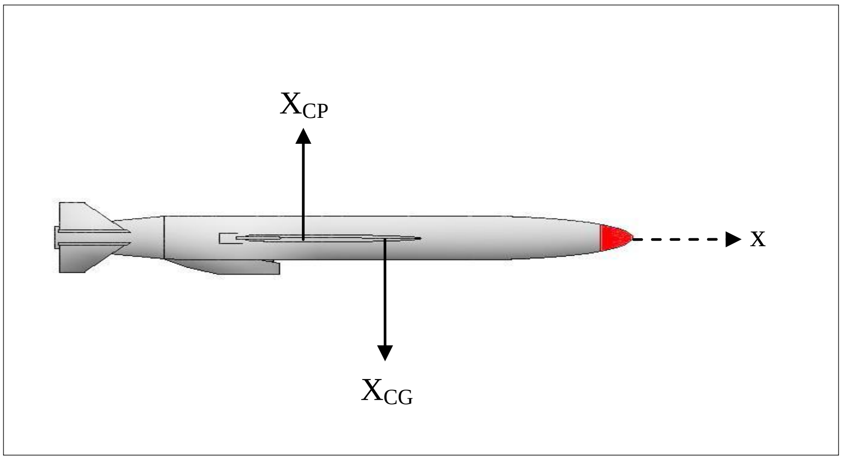


Figure 3.8 *CG* and C_P Locations for a Statically Stable Missile

To sum up, to keep a negative slope of the pitching moment coefficient versus angle of attack curve is a strict constraint for the candidate missile at the current design stage.

3.4.2 Control Effectiveness

Control effectiveness is such a vital parameter that has to be considered early in conceptual design. Controllability can be defined as the effect of control surface deflections to the pitch, roll and yaw angles of the missile. In other words, it determines how much angle of attack is obtained by creating fin deflections. As stated earlier, pitch moment is the main concern in this thesis. Therefore only the control effectiveness in pitch plane is the main interest for the time being.

A rule of thumb for conceptual design of a tail controlled missile is that the change in angle of attack due to control deflection should be greater than unity to have adequate control margin [1].

$$\frac{C_{m_\delta}}{C_{m_\alpha}} = \frac{\Delta C_m}{\Delta \delta} \frac{\Delta \alpha}{\Delta C_m} = \frac{\Delta \alpha}{\Delta \delta} > 1 \tag{3.13}$$

3.4.3 Total Mass

Weight is one of the major constrains of the conceptual design optimization problem. It is necessary to develop an approach to estimate the missile launch weight which is considered to be the input for a new design in the conceptual design phase. Although there has been extensive work in the field of weight estimation equations for aircraft, there has been comparatively little work performed, at least in the open literature for missiles. John B. Nowell Jr., in his study named "Missile Total and Subsection Weight and Size Estimation Equations", offers an empirical approach using statistical regression analysis of historical missile data in order to develop equations for the different physical properties of the missile and its subsections based on the rationale that since these parameters were justified during each previous missile's own design process. Then the relations obtained using the data should be applicable to new designs [39]. His methodology is applied for several existing air-to-ground missiles and the obtained results and error bounds are in such a way that this approach is applicable for the solution of the missile weight prediction problem.

In this approach for the weight prediction, the generic missile is examined in four subsections namely as propulsion, guidance and control, warhead sections and wing and tail surfaces as illustrated in Figure 3.9.

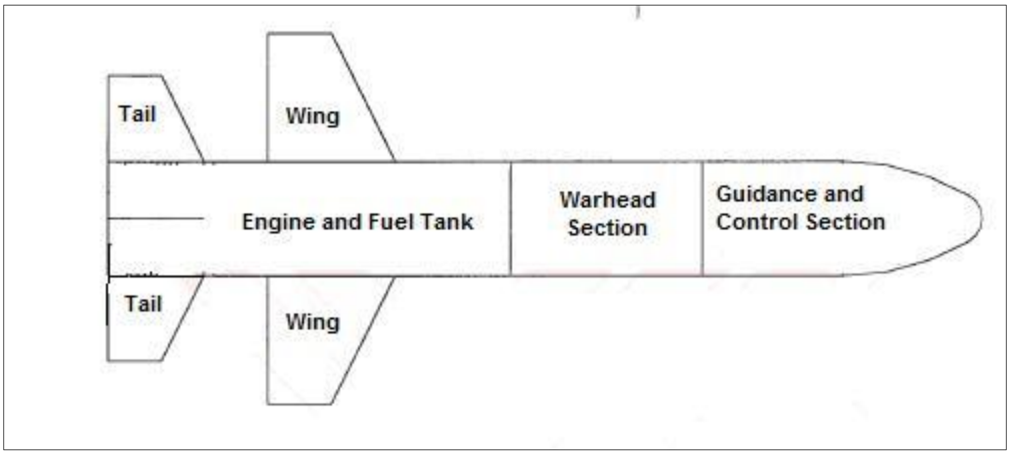


Figure 3.9 Generic Air-to-Ground Missile Subsections

For the weight prediction of each subsection, empirical methods of statistical regression analysis are utilized to generate the equations relating the overall missile and subsection geometries and weights to design variables such as missile length weight, diameter, flight range and speed in units feet, knots and nautical mile, respectively.

Before proceeding, an initial estimation for the total missile weight is needed. This is accomplished by using the equation below [39].

$$W_M = 118.5(Vol_M)^{0.84} \tag{3.14}$$

where the variable Vol_M is the total volume of the missile and it can be calculated by CAD tools.

Although it is made possible to estimate the weights of the subsections, the center of gravity location is another conflict for the case because the exact location of the center of gravity of the missile is directly related with the interior design of the missile. Throughout the concept of this work, the optimum external configuration of the missile is intended as a request of the conceptual design phase. The detailed interior design is considered to be left to the preliminary design stage. Consequently, it is assumed that the interior design of the missile is adjusted in such a way that the center of the gravity of the missile is at the half of the total length of the missile measured from the nose. Additionally, an assumption is made such that the center of gravity of the fuel is so close to the center of gravity of the missile that the change of the center of gravity location during the flight could be neglected.

3.5 Design of Experiments (DOE)

In order to create the initial design points which homogeneously cover the design space, DOE approach is widely used as a systematic way. Using a formal and efficient approach, DOE is necessary for modern optimization studies to get more information from limited sources. Also, DOE method is more useful for judgment of the effects of input parameters on the outputs than changing one parameter at one time method. "One change at one time" method which has been used in classical optimization studies, could not investigate the combined effects of input parameters. However, DOE creates optimum design points homogeneously covering the design space with all possible dependencies. In post processing stage of design, all of the needed data are collected and combined effects easily investigated using proper DOE algorithm.

In this study, in order to define main effects of inputs on responses (outputs) Full Factorial designs have been used which is shown in Figure 3.10. Full factorial design of experiment algorithm creates all possible combinations of design parameters with given increments. The increments define the parameter investigation level. For example, if a design parameter has lower and upper bounds varying from 1 to 3 and the increment level is 1, then full factorial DOE algorithm creates 3 design points. If there are 3 design variables with increment levels of 3, 4 and 5, there are 3x4x5=60 experiments. Using full factorial DOE algorithm, designer gets equal sufficient experiments to identify all interactions and defines all main effects of input parameters on objectives.

Also, with the intention of defining initial design points of genetic optimization algorithm, Sobol DOE method has been used which is also shown in Figure 3.10. Sobol's pseudo random sequence was first introduced for Monte Carlo integration by I. M. Sobol in 1967 [40] [41]. The sequence generates numbers between zero and one in an S-dimensional space. Successive points fill in the gaps perfectly. The main feature of the Sobol's sequence is a better uniformity of points compared with a random sequence with uniform distribution. Sobol and random sequences are shown in Figure 3.10.

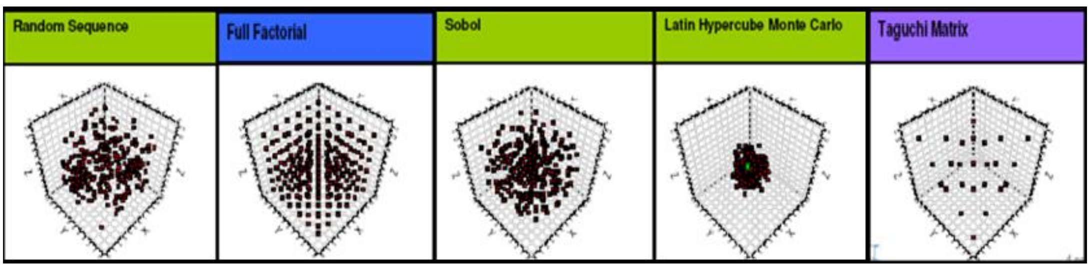


Figure 3.10 Design of Experiments Methods

3.6 Optimization Algorithm

Multi Objective Genetic Algorithm (MOGA-II) with a simple constraint handling method is applied to find Pareto optimal solutions of this bi-objective optimization problem. MOGA-II is one of the evolutionary algorithms which involve elitism sorting procedure in every generation; by using this algorithm one can prevent the loss of good solutions once they are found [42].

In the case of a single objective, the elitism can be easily defined, identifying it with the operator that preserves and copies to the next generation the solution with the best fitness.

The problem of defining suitably, the elitism arises in the context of a multi-objective algorithm, where there is more than one objective function and it is possible to have more than one elite solution.

In the case of multiple objectives, it is good to introduce the concept of Pareto optimality, and the correlated idea of dominance: by definition, Pareto solutions are consider optimal because there are no other designs that are superior in all objectives.

3.6.1 Pareto Optimal

Suppose it is desired to maximize all f_i, a decision vector $x^* \in S$ is Pareto Optimal if there does not exist another decisiton vector $x^* \in S$ such that $f_i(x) \geq f_i(x^*)$ for all $i=1,2,3,...,k$ and $f_j(x) \geq f_j(x^*)$ for at least one index j:

Mathematically, every Pareto optimal point is an equally acceptable solution for a multi-objective optimization problem.

3.6.2 Dominance

A decision vector x dominates another decision vector *y* if $f_i(x) \geq f_i(y)$ for all *i=1,2,3,...,k* and $f_j(x) \geq f_j(x^*)$ for at least one index j:

This definition can be easily explained with a simple example. In Figure 3.11, it is presented a point A in a two-objective (*f1* and *f2*) optimization problem. The point A defines two zones: the shaded one (i.e. the left-bottom quadrant) represents the set of the dominated points, while the complementary area (i.e. the whole of the other three quadrants) represents the set of the non-dominated points. If A is a point of the previous generation and the actual generation contains the point B, then the new position is a very favorable one: not only B is non-dominated by A, but even B dominates A. This kind of evolution is always desirable, and this transition has certainly to be preserved. If the evolutions bring A to C (or C'), the new point is however a non-dominated one: in this case the transition should be preserved too, in order to favor the spread of the points along the Pareto frontier. The elitism in this new version of the multi-objective genetic algorithm is applied as follows [42]:

1. Begin with starting populations and size *P, N* and with the elite set $E = \emptyset$
2. Then calculate $P' = P \cup E$
3. If P' is better than the impotence of *P*, reduce P' removing randomly the exceeding points
4. Calculate P' to P''
5. Compute the fitness for the population P''
6. Copy all non-dominated designs of P'' to *E*
7. Remove duplicated from *E*

8. Resize the elite set *E*
9. Check size of *N* if it bigger than desired remove randomly the exceeding points
10. Go to step 2 with P'' as the new *P*

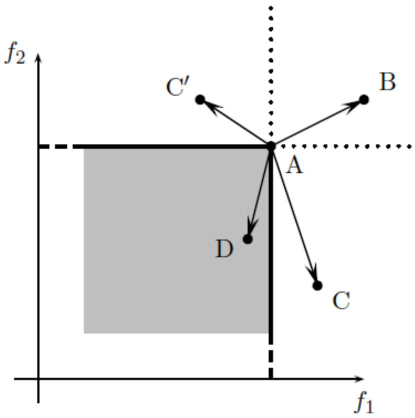


Figure 3.11 Dominated and Non-dominated Points [42]

As seen from Figure 3.11 the point A splits this two dimensional objectives space in two zones: the set of the dominated points is represented by the shaded area. A dominates D, while B, C and C' are non-dominated.

CHAPTER 4

CASE STUDY

In this section, a case study is employed in order to verify the methodology given in previous chapters. In order to find global optimum with respect to electromagnetics and flight performance objectives in the feasible design region, for a generic air-to-surface, turbojet powered missile geometrical parameters are multi-disciplinary optimized. Results are compared with some validated air-to-surface missiles which are used in real military operations. The benchmarked missiles are Taurus KEPD 350, NSM and Storm Shadow [43], [44], [45]. These missiles are designed with respect to high survivability and long range requirements, thus comparison with these missiles are meaningful for validation of the optimization methodology.

As stated in Section 3.1.1 baseline missile has external geometry parameters as body cross sectional shape (circular and elliptic), for elliptic body shapes ellipticity factor is also a parameter, missile tail and wing span, nose and body section lengths, wing and tail sweeps, wing and tail chords and thicknesses. The summary of external body parameters are given in Figure 4.1.

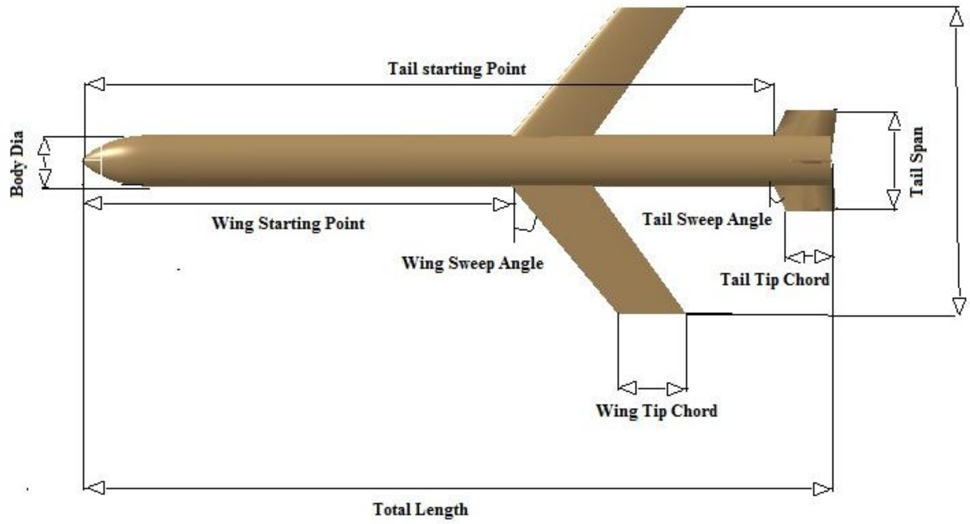


Figure 4.1 External geometry parameters

In addition to these parameters, for wing according to known air-to-surface missile geometries, NACA-1-6-65-410 profile is used, and for tails hexagonal tail profile whose details are given in Figure 4.2 is used. These parameters are specifically selected for case study, however for other cases different selections could be made.

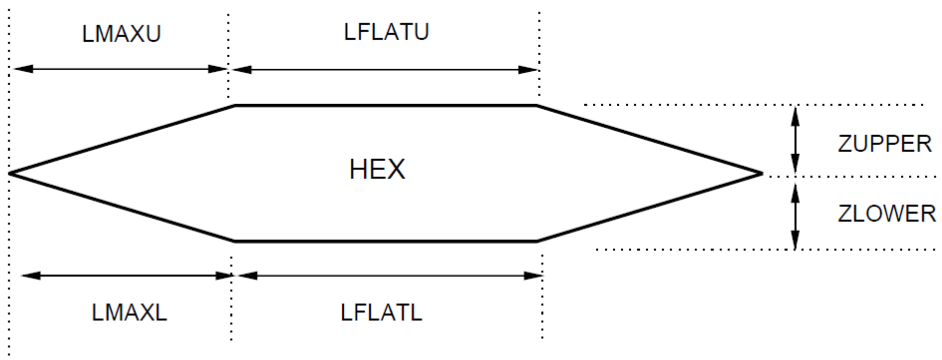


Figure 4.2 Hexagonal profile parameters

Given external geometry parameters are bounded with respect to physical constraints. These upper and lower limits of parameters are summarized in Table 4.1.

Table 4.1 Upper and Lower Bounds of Geometric Parameters

Definition	**Upper Bound**	**Lower Bound**
Total length (mm)	2000	4000
Nose length (mm)	100	600
Ellipticity (height/width)	0.5	2
Body Dia (mm)	300	800
Wing tip chord (mm)	100	600
Tail tip chord (mm)	100	500
Tail root profile half thickness (mm)	10	20
Tail tip profile half thickness (mm)	10	20
Wing half span (mm)	400	1500
Tail half span (mm)	100	500
Wing starting point (mm)	500	4000
Wing sweep angle (^{o})	0	45
Tail sweep angle (^{o})	0	45
Tail configuration (plus or cross)	1	2

Before starting the analyses missile mission profile is necessary to define flight conditions to employ three degree of freedom simulation and radar detection angles. According the researches in literature, for turbojet powered air-to-surface possible missile trajectory profile is given in Figure 4.3.

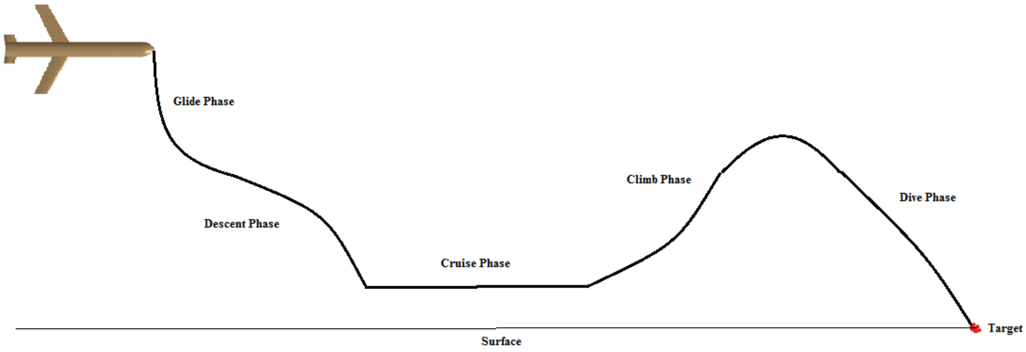


Figure 4.3 Mission profiles

4.1 Optimization Results

The optimization algorithm's parameters and DOE information are given in Table 4.2. As shown from the table, there are 2491 unique models and all of them are evaluated with respect to given objectives and constraints. Because there were lots of design constraints which restrict the design area, unfeasible designs cover large percentage of all of the design space.

Table 4.2 Optimization Algorithm and DOE Algorithms Parameters

Parameters	Value
Number of Generations	100
DOE number	100 (Sobol's Algorithm)
Selection Probability	0.05
Mutation Probability	0.1
Directional Cross-Over Probability	0.5
Number of All Designs	2491
Number of Feasible Designs	559

4.2 Residuals

Optimization results with respect to given objectives, radar cross section and range, versus to design number which is a given number for every individual design called design ID are given in Figure 4.4 and Figure 4.5. Scatter chart radar cross section respect to flight range is also given in Figure 4.6.

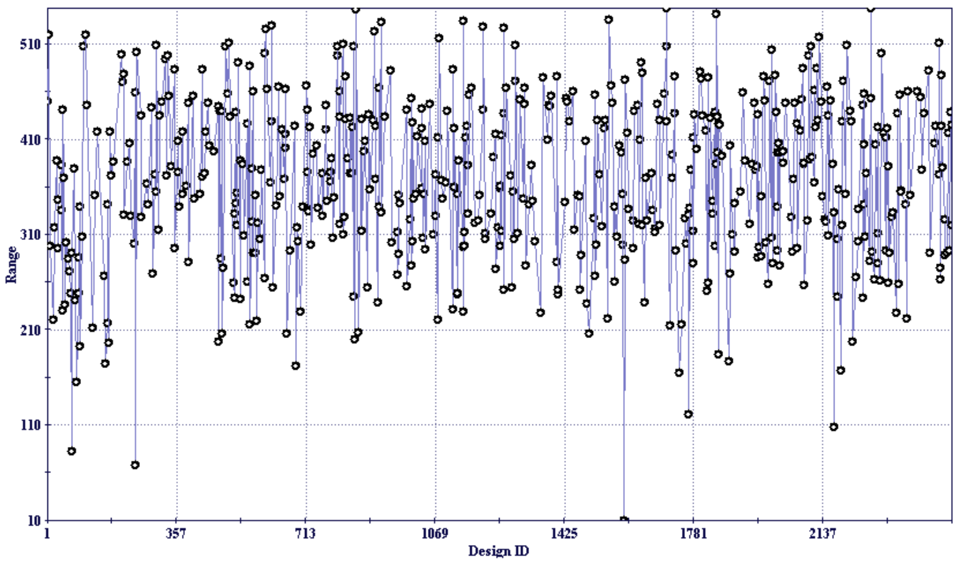


Figure 4.4 History graphics of flight range

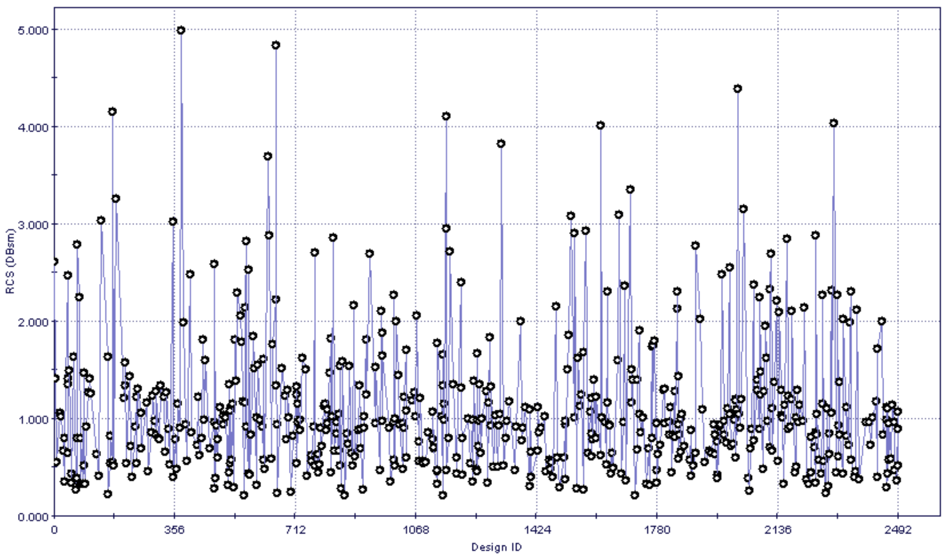


Figure 4.5 History graphics of RCS

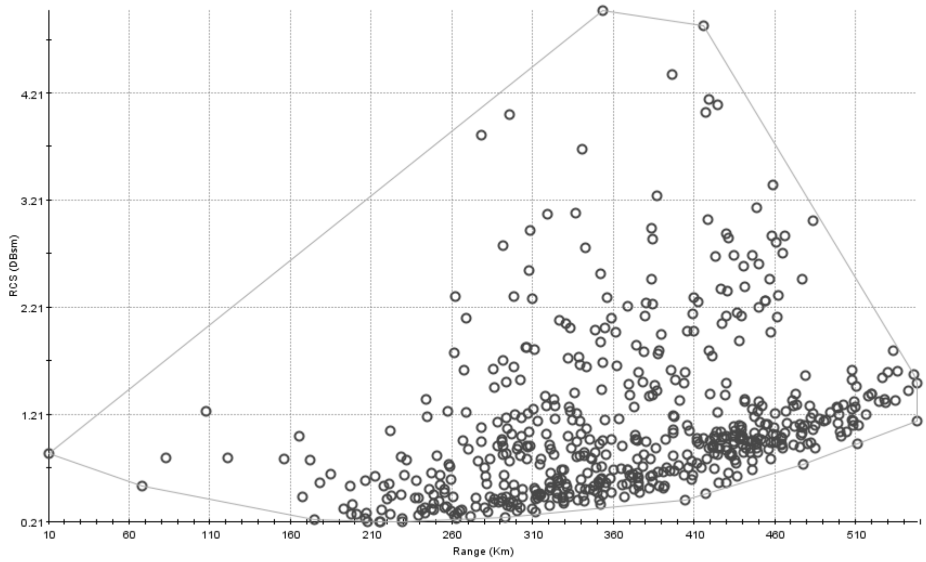


Figure 4.6 Range versus RCS

4.3 Main Effects

Main effects of input parameters on responses (radar cross section and range) are shown in Figure 4.7, Figure 4.8, Figure 4.9, Figure 4.10, Figure 4.11, and Figure 4.12. Investigation of main effects is important to define effects of parameters on objective before starting the optimization study. Some parameters could be more effective on objectives than the others, thus designer should choose search step for more effective parameters smaller and for less effective parameters larger.

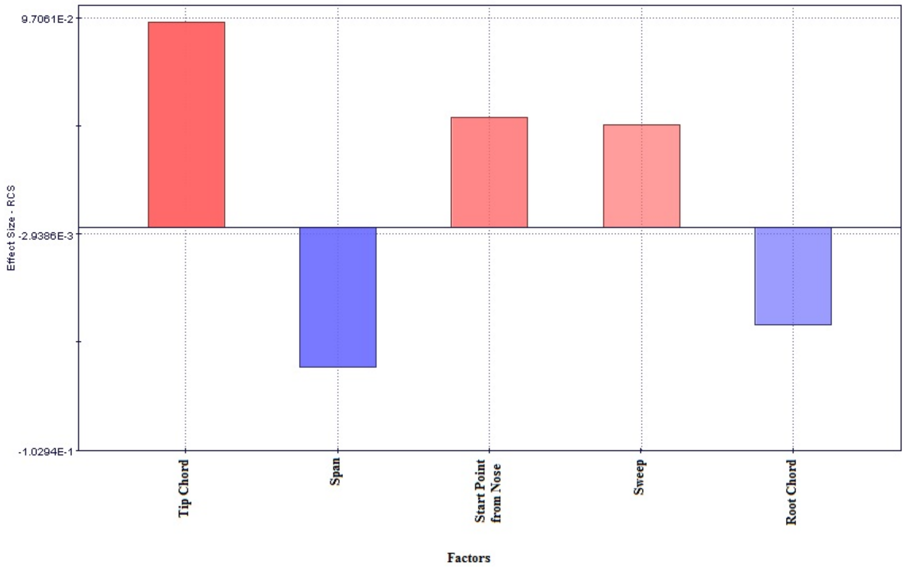


Figure 4.7 Wing main effects on RCS

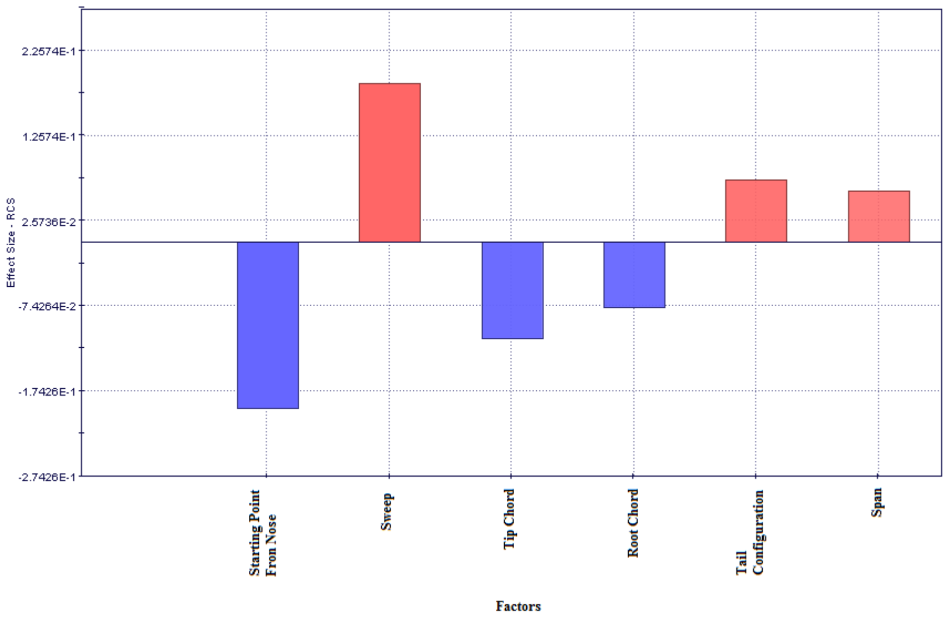


Figure 4.8 Tail main effects on RCS

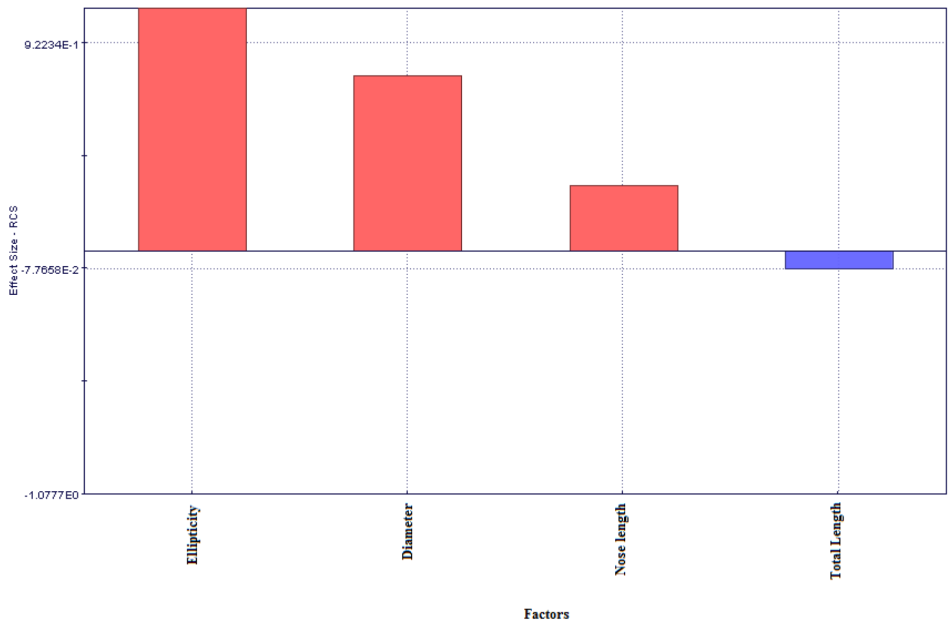


Figure 4.9 Body main effects on RCS

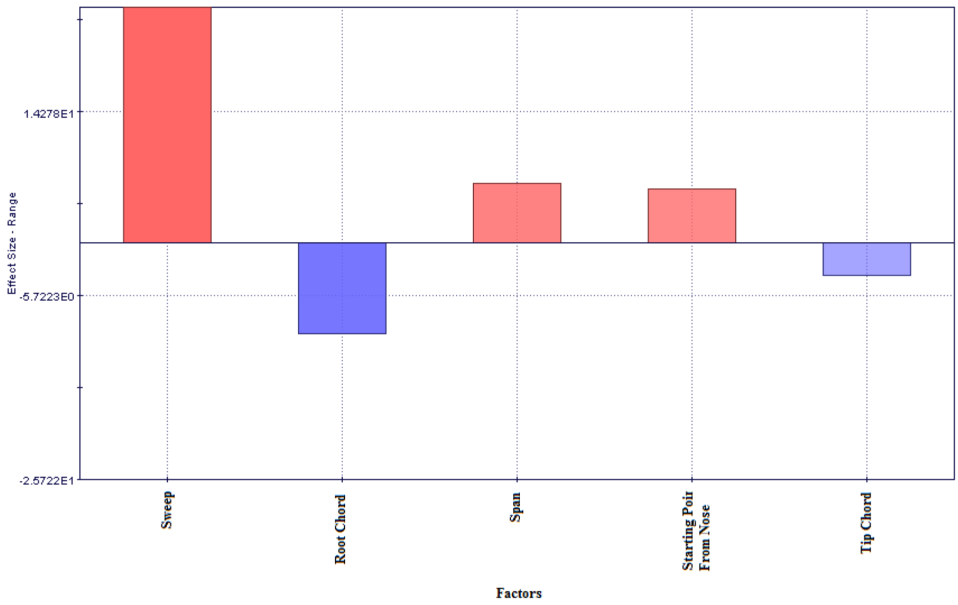


Figure 4.10 Wing main effects on flight range

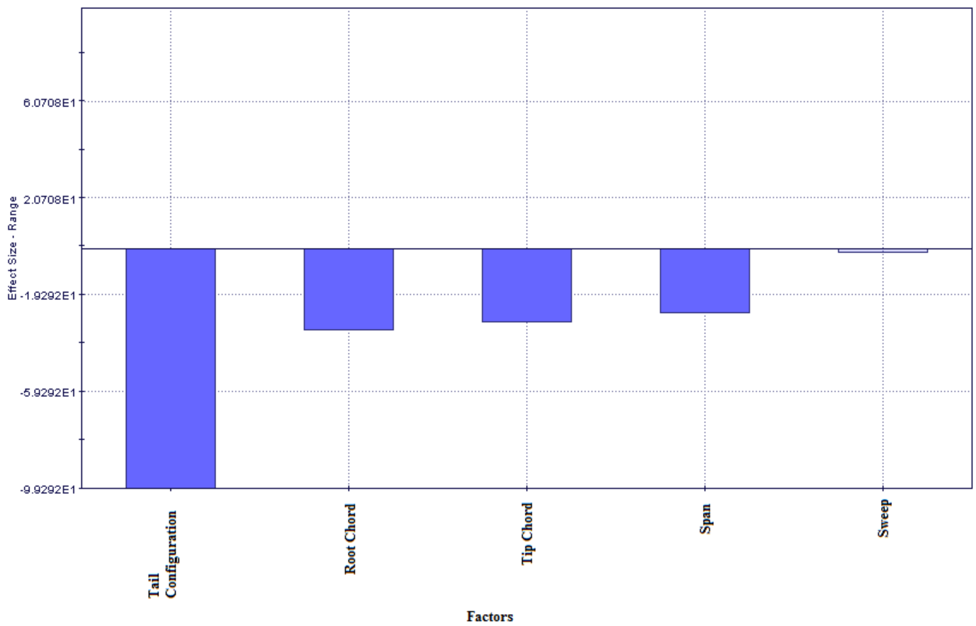


Figure 4.11 Tail main effects on flight range

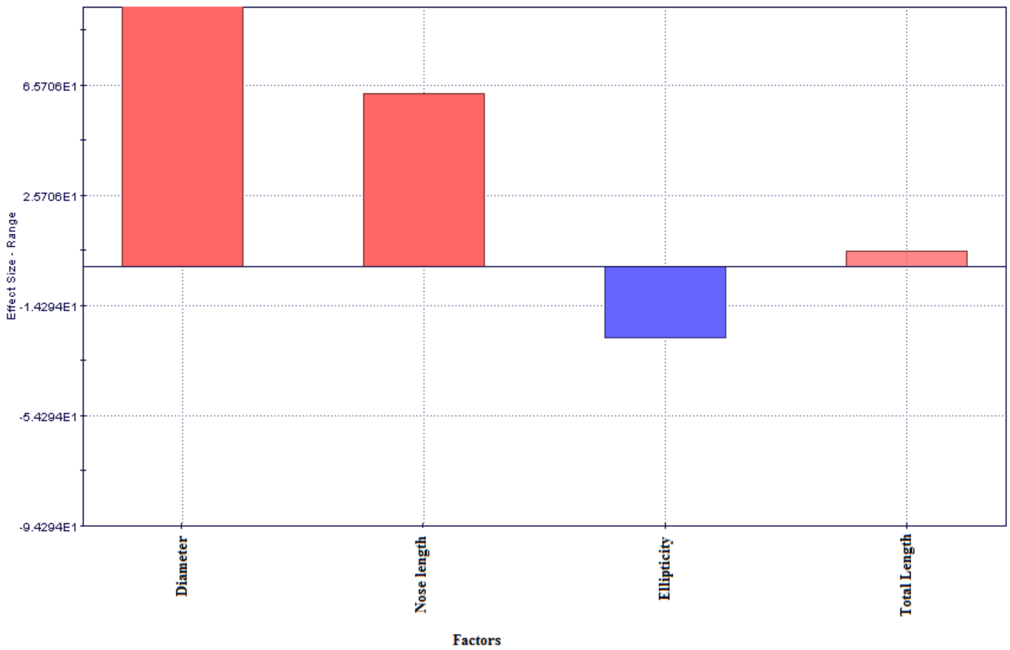


Figure 4.12 Body main effects on flight range

4.4 Pareto Optimal Solutions

Definition of pareto is given in Section 3.5.1. Trough this definition pareto optimal solutions of optimization results listed and shown in Figure 4.13.

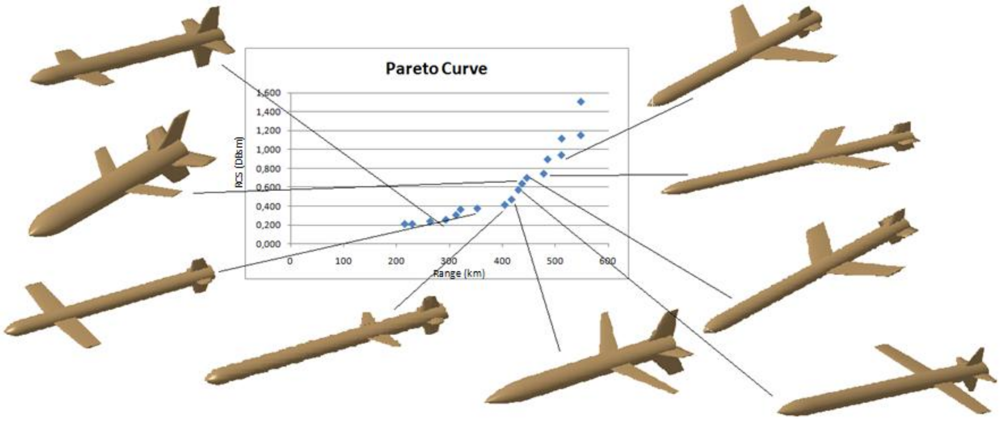


Figure 4.13 Pareto optimum solutions

4.5 Comparison of Results with Validated Missiles

Because design space is very large and widespread design requirements for decision making, before compare the results and decide the optimum configuration, Missiles which are being compared with each other should be grouped. The main objective of missiles in preliminary design phase mostly is the flight range. Thus, missiles firstly grouped by missile ranges and relatively grouped by missile total mass (Table 4.3). As stated, previous stages of this section missile which are desired to be compared with results of this study are Taurus KEPD 350, NSM and Storm Shadow. Information about these missiles collected from open sources in literature and similar groups with pareto optimal solutions are compared with each other.

Table 4.3 Missile Classification

	Range	**Weight**
Huge Size Missiles	>500 km	>500kg
Medium Size Missiles	200km-500km	200kg-500kg
Small Size Missiles	<200km	<200kg

Figure 4.14 Naval Strike Missile (NSM)

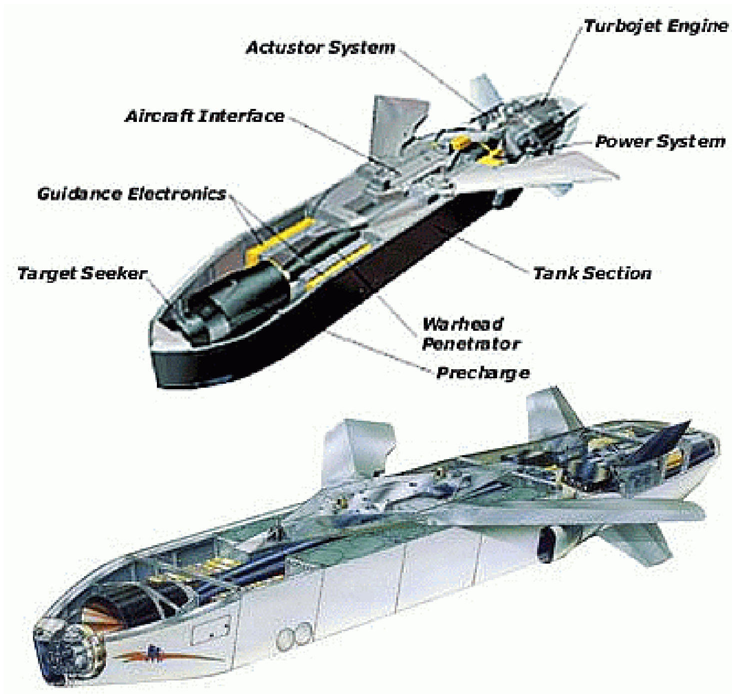


Figure 4.15 Taurus KEPD 350

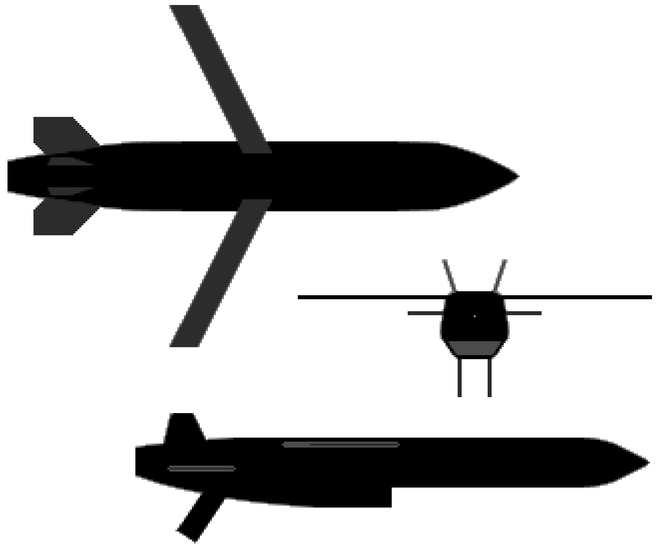


Figure 4.16 Storm Shadow

According to comparison of KEPT 350 with Pareto1, Pareto2 and Pareto 3 (Table 4.4) validated missile wing and tail parameters are similar but length and diameter are greater than the design results. The error between Pareto3 and KEPT 350 for wing root chord is lower than %5 and for tail span lower than %8.

Table 4.4 Taurus KEPD 350 Comparison Results

	Pareto1	**Pareto2**	**Pareto3**	**TAURUS**
Wing Root Chord	0,482	0,431	0,600	0,630
Wing Tip chord	0,345	0,305	0,391	0,150
Tail Root chord	0,202	0,271	0,309	0,260
Tail Tip chord	0,118	0,181	0,198	0,130
Ellipticity	0,500	0,500	0,500	-
Total Length	3,083	3,534	3,500	5,100
Nose Length	0,533	0,461	0,562	-
Wing span	0,845	0,747	0,869	1,031
Tail Span	0,289	0,248	0,257	0,133
Wing Sweep	40	40	45	-
Tail Sweep	10	10	20	-
Diameter	0,468	0,445	0,440	1,080
Wing Start Point	2,400	2,200	1,900	-
Tail Sweep	3,413	3,725	3,753	-
Tail Configuration	1,000	1,000	1,000	-
Control effectiveness	0,73	0,285	0,44	-
Stability	-2,230	-1,249	-0,801	-
Total Mass	878	875	869	1400
Flight Range	512	511	485	500
RCS	1,116	0,942	0,896	-

Table 4.5 Storm Shadow Comparison Results

	Pareto4	Pareto5	Storm Shadow
Wing Root Chord	0,563	0,563	0,145
Wing Tip chord	0,189	0,383	0,255
Tail Root chord	0,331	0,261	0,160
Tail Tip chord	0,199	0,166	0,090
Ellipticity	0,500	0,500	-
Total Length	3,329	3,073	5,100
Nose Length	0,594	0,600	-
Wing span	0,808	1,061	1,420
Tail Span	0,296	0,402	0,170
Wing Sweep	30	35	-
Tail Sweep	10	15	-
Diameter	0,316	0,304	0,480
Wing Start Point	2,000	2,300	-
Tail Sweep	3,593	3,412	-
Tail Configuration	1,000	1,000	-
Control effectiveness	0,124	0,1004	-
Stability	-1,784	-10,861	-
Total Mass	433	376	1230
Flight Range	263	229	250
RCS	0,239	0,212	-

In addition, the comparison between Pareto 6 and NSM show that Pareto6 have 215 km range and NSM have 185 km range, this presents +%13 difference between real and designed missiles, however NSM is heavier and longer (Table 4.6).

Table 4.6 NSM Comparison Results

	Pareto6	**NSM**
Wing Root Chord	0,458	0,600
Wing Tip chord	0,354	0,200
Tail Root chord	0,313	0,380
Tail Tip chord	0,183	0,150
Ellipticity	0,500	1
Total Length	2,702	3,960
Nose Length	0,493	-
Wing span	0,766	0,835
Tail Span	0,272	0,400
Wing Sweep	40	-
Diameter	0,303	-
Wing Start Point	1,800	-
Tail Sweep	2,883	-
Control effectiveness	0,361	-
Stability	-4,107	-
Total Mass	326	410
Flight Range	215	185
RCS	0,211	-

The similar situation with NSM is true for Storm Shadow. There would be reasonable distinctions in the external shapes of the missiles with compared ones if the re-configuration problem were not employed with specific constraints and weighting factors.

CHAPTER 5

CONCLUSION

This thesis presents a multi disciplinary optimization technique which is utilized for the conceptual design optimization problem of a generic air to ground missile. To initiate the design cycle, a baseline missile external configuration is specified with two wings and four tails powered with a turbojet engine. Some critical design objectives such that the mission profile desired to be flown, the range desired to be reached and the launch mass are all left to the designer to be determined at the beginning of the whole process. In addition to these, the geometric constraints for the sake of launch compatibility are the essential inputs for the optimization algorithm. Optimization algorithm is MOGA II which is a multi objective genetic algorithm and details and results were given.

To decide up the optimal missile geometry that meets best with the user defined requirements, a simulation tool is implemented with three degrees of freedom flight mechanics model that consists of equations of motion, aerodynamics, turbojet, control and atmosphere models. The usage of a three degree of freedom model brings the advantage of the fast evaluation of the flight performance of the candidate missile. At each step of the iteration, the candidate missile is checked whether it satisfies the geometrical constraints as well as the upper and lower bounds for each external configuration parameter. If so, the flight performance parameters, namely the flight range, radar cross section, launch weight, longitudinal stability and controllability are determined as a result of the flight simulation.

Moreover, the aerodynamic database for the external geometry is also generated in each function evaluation by using the Missile DATCOM aerodynamic prediction tool.

Since the conceptual design stage is the starting point for a whole missile design process, it is aimed to carry out two main objectives: maximum flight range with minimum radar cross sectional area. Results of the study present pareto optimal solutions which are applicable for all changing requirements and desired missile classifications.

Pareto optimum solutions are predictions of an existing cruise missile configuration, so they are compared with validated missiles such as KEPD 350, NSM and Storm Shadow. The benchmark cases, which are turbojet powered air to ground missiles with two wings and four tails configuration, are selected. The conceptual multi disciplinary design optimization methodology is executed for the two objectives equally weighted to get pareto solutions. The outcome for the flight performance, radar cross section and the external configuration parameters are compared with ones which are able to be found for the existing missile. In addition, to define more and less effective variable, a main effect study is employed and results are given.

Benchmark study is employed after the obtained pareto optimum solutions are grouped with respect to range and weight. Comparison and discussion of results are handled between same grouped missiles.

The obtained results prove that the methodology is capable of finding an optimal external missile configuration satisfying the user defined requirements and constraints in short durations. This plays a vital role in the missile design processes since it reduces the effort and time to find out the optimum baseline geometry throughout a huge design domain.

There are some differences in external geometries between real and designed missiles. Number of differences can be higher when the number of unknown constraints in the re-design process is increased. In general, it is impossible to know all the real-life constraints faced with during a real design and manufacturing process of a missile. In this study, most of the subsystem constraints related to warhead, guidance-control section, and seeker are not taken into account. However, these constraints have additional impacts on the warhead effectiveness, lethality as well as producibility of the missile. In addition to them, the radar cross section area calculations and requirements which affect the radar detection probability of the missile changes one military operation to another. For instance, some missiles are mostly used for monostatic radar area and others are used for bi-static radar areas. Although they have impacts on the final geometry of the optimum missile, these constraints on the baseline missile benchmark missiles cannot be obtained from open sources.

Several recommendations for the future improvements of the methodology are listed as below.

- A more complicated dynamic model with six-degree of freedom could be implemented in order to investigate the lateral dynamics and performance of the missile. By this way roll and yaw properties to the missile are able to be considered.

- The design objectives could be increased. Minimizing the radar cross section (RCS), maximizing the hit accuracy and warhead effectiveness could also be taken into account as design objectives.

- The specification for the turbojet engine could be automized. The turbojet engine that provides the necessary requirements would be specified that suits geometrically with the designed missile.

- The concept of the conceptual design optimization of an air to ground missile could be extended to cover other types of missiles like air to air and surface to air missiles.

- Use of CFD calculations could be included to define aerodynamic coefficients.

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APPENDIX A

MISSILE DATCOM INPUT FILE

```
CASEID SAMPLE
DIM CM
DERIV RAD
$REFQ
 SREF=855.3, LREF=16.5, LATREF=16.5, XCG=179.0, ZCG=0.0,
 BLAYER=NATURAL, RHR=400.0, SCALE=1.0,
$END
$AXIBOD
 TNOSE=OGIVE,
 POWER=1.0,
 LNOSE=21.0,
 DNOSE=33.0,
 LCENTR=315.0,
 DCENTR=33.0,
$END
$FINSET1
 SECTYP=NACA,
 CHORD=52.0,29.0,
 SSPAN=0.0,37.0,
 XLE=182.0,
 STA=0.,
 SWEEP=41.0,
 NPANEL=2.0,
 PHIF=90.0,270.0,
 GAM=0.,0.,
$END
NACA-1-6-65-410
$FINSET2
 SECTYP=HEX,
 SSPAN=0.0,19.0,
 CHORD=19.0,19.0,
 XLE=338.0,
 SWEEP=0.0,
 STA=0.,
 NPANEL=4.0,
 PHIF=0.0,90.0,180.0,270.0,
 GAM=0.,0.,0.,0.,
$END
$FLTCON
 NMACH=10.0,
```

```
 NALPHA=10.0,
 MACH=0.1,0.3,0.5,0.6,0.7,0.8,0.9,1.0,1.2,1.4,
 ALT=100.0,100.0,100.0,100.0,100.0,100.0,100.0,100.0,100.0,100.0,
 ALPHA=-10.0,-7.0,-4.0,-2.0,0.0,2.0,4.0,6.0,8.0,10.0,
$END
$FLTCON
 BETA=0.,
$END
$DEFLCT
 DELTA2=10.,10.,-10.,-10.,
$END
DAMP
SAVE
NEXT CASE
$DEFLCT
 DELTA2=5.,5.,-5.,-5.,
$END
DAMP
SAVE
NEXT CASE
$DEFLCT
 DELTA2=0.,0.,0.,0.,
$END
DAMP
SAVE
NEXT CASE
$DEFLCT
 DELTA2=-5.,-5.,5.,5.,
$END
DAMP
SAVE
NEXT CASE
$DEFLCT
 DELTA2=-10.,-10.,10.,10.,
$END
DAMP
SAVE
NEXT CASE
```