# MULTIDISCIPLINARY DESIGN, OPTIMIZATION AND PERFORMANCE ANALYSIS TOOL FOR BALLISTIC MISSILES

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**MULTIDISCIPLINARY DESIGN, OPTIMIZATION AND PERFORMANCE ANALYSIS TOOL FOR BALLISTIC MISSILES**

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# ABSTRACT

## MULTIDISCIPLINARY DESIGN, OPTIMIZATION AND PERFORMANCE ANALYSIS TOOL FOR BALLISTIC MISSILES

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Missile system design process is challenging and interdisciplinary. During missile system design process, system design must be made in accordance with military standards, which have very strict rules.

In defense industry, delivery dates are usually very rigid. Despite this, during conceptual design, requirements are often updated within the design process that requires the design to be updated frequently. It is essential to perform these steps as efficiently and quickly as possible.

The products, which are inexpensive and have best performance parameters, are preferred, and so the companies with these products can survive. For this purpose, the conceptual design part, which is first step of the system design process needs to be optimized.

In this study, it is aimed to develop a system design tool that simplifies the conceptual design process, creates design alternatives quickly, tests them, performs performance analysis, and selects the optimum among these alternatives. By using this tool, it is possible for the designer to obtain the information needed for the preliminary design process quickly and efficiently.

This thesis focuses on ballistic missile systems, which are widely used in today's world and expected to increase in number over time. It is aimed to accelerate the conceptual design process of ballistic missile systems. For this purpose, to create optimum alternative design which has maximum ballistic range and maximum maneuverability, an optimization tool for conceptual design studies is created.

**Keywords:** Ballistic Missiles, Genetic Algorithm, Maneuverability, Optimization

# ÖZ

## BALİSTİK FÜZELER İÇİN DİSİPLİNLER ARASI TASARIM, ENİYİLEME VE PERFORMANS ANALİZ ARACI

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Füze sistem tasarım süreci zorlu ve disiplinler arası bir süreçtir. Füze sistemi tasarım sürecinde, sistem tasarımı çok katı kuralları olan askeri standartlara uygun olarak yapılmalıdır.

Savunma sanayinde teslimat tarihleri genellikle çok katıdır. Buna rağmen, kavramsal tasarım sırasında, gereksinimler sıklıkla güncellenir. Gereksinimlerin göz önüne alındığı ilk adım olan kavramsal tasarım sürecini mümkün olduğu kadar verimli ve hızlı bir şekilde gerçekleştirmek çok önemlidir.

Ucuz ve en iyi performans parametrelerine sahip olan ürünler tercih edilir ve bu ürünlere sahip şirketler hayatta kalabilir. Bu amaçla, sistem tasarım sürecinin ilk adımı ve sistem tasarımının en önemli bölümlerinden biri olan kavramsal tasarım sürecinin optimize edilmesi gerekir.

Bu çalışmada, kavramsal tasarım sürecini basitleştiren, hızlı bir şekilde tasarım alternatifleri yaratan, yaratılan her bir alternatifi test eden, performans analizi yapan ve bu alternatifler arasından en iyi olanı seçen bir sistem tasarım aracı geliştirilmesi amaçlanmaktadır. Bu aracı kullanarak, tasarımcının ön tasarım çalışmaları için gerekli bilgileri hızlı ve verimli bir şekilde elde etmesi mümkündür.

Bu tez balistik füze sistemlerine odaklanmaktadır. Balistik füzeler günümüz dünyasında yaygın olarak kullanılmaktadır ve zamanla sayısının artması beklenmektedir. Balistik füze sistemlerinin kavramsal tasarım sürecini hızlandırmak amaçlanmaktadır. Bu amaçla, maksimum balistik menzile ve maksimum manevra kabiliyetine sahip, optimum alternatif tasarımı oluşturmak için bir tasarım aracı yaratılmıştır.

**Anahtar Kelimeler:** Balistik Füzeler, Genetik Algoritma, Manevra Kaabiliyeti, En iyileme

***To My Lovely Parents***

***Müge & Ayhan ADSIZ***

***To My Beloved Love***

***Çağrı TEPE***

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SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| $\alpha$ | angle of attack |
| $\theta$ | Euler angle in pitch plane |
| $\delta$ | deflection angle |
| $C_{X_b}$ | force coefficient in the *x* direction in boost phase |
| $C_{X_C}$ | force coefficient in the *x* direction in coast phase |
| $C_m$ | pitching moment coefficient |
| $C_{m_\alpha}$ | pitching moment coefficient with respect to angle of attack |
| $C_{m_q}$ | pitching moment coefficient with respect to pitching moment |
| $C_{m_\delta}$ | pitching moment coefficient with respect to deflection angle |
| $C_N$ | normal force coefficient |
| D | total drag force |
| DOF | degree of freedom |
| $F_{aero}$ | aerodynamic forces |
| $F_x$ | x axis force Component in body frame |
| $F_z$ | z axis force Component in body frame |
| $g$ | gravitational acceleration |
| $I_{yy}$ | principle inertia term |
| L | total lift force |
| $L_{ref}$ | reference length of missile |

| | |
|---|---|
| m | mass of the missile |
| $M_y$ | y axis moment component in body frame |
| $M_{aero}$ | aerodynamic moments |
| n | load factor |
| N | total normal force |
| $q$ | pitching moment |
| Q | dynamic pressure |
| $S_{ref}$ | reference area of missile |
| SM | static margin |
| $u$ | x axis velocity component in body frame |
| $w$ | z axis velocity component in body frame |
| $V_P$ | propulsion volume |
| $V_T$ | total velocity |
| $V_{Total}$ | total missile volume |
| $V_\infty$ | freestream velocity |
| $W_p$ | propulsion weight |
| $W_{Total}$ | total missile weight |
| $X_{c.g}$ | missile center of gravity |
| $X_{c.p}$ | missile center of pressure |
| $\rho_\infty$ | freestream density |
| $\rho_{Total}$ | total missile density |

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction to the Problem

In these days, multidisciplinary design and optimization of aircraft vehicles attract many designers and companies. An engineering design optimization problem is defined as getting the best possible system design under given requirements, constraints and time interval. In addition, aircraft system design, almost all system includes subsystems, which are used to satisfy the performance parameters, allocated it, so in other words aircraft vehicles can be defined as systems of systems. Because of this reason, aircraft systems design process requires multidisciplinary and multi-objective optimization. Design engineers usually need a tool to overcome these design optimization problems in a limited time.

In missile system design process, it is necessary to analyze large design space. Number of input variables is important for the complexity of the design space. For aerodynamic design, missile diameter, missile length, nose length, body length, number of fin sets, fin set locations, size and shape of each fin sets are some of the important examples of the input variables. Moreover, aerodynamic performance parameters, geometric limitations, cost and time limits are also important parameters for the system design process. For these reasons, to overcome the difficulties system design process should be optimized.

Conceptual design which is the first part of the design process is very important due to the required information for the preliminary design studies are provided in that step. However, there exist numerous variables, constraints and performance parameters and these are made the problem difficult to solve in limited time. When the quicker and more accurate the conceptual design phase, the more accurate information is fed into the ongoing step.  So, the redundant iterations are eliminated.

In the conceptual design studies, the most important performance parameters are range, maneuverability, stability and control effectiveness. These parameters are directly related to the external geometry of the missile. When the external geometry optimized, the performance parameters are optimized too.

## 1.2 Literature Survey

Aircraft design is a complex multidisciplinary process. When the literature survey is conducted, it is observed that some system design tools for the conceptual design stage existed. The first one is developed by Bennett, Low Observables Design Synthesis Tool (LODST), which creates arbitrary body shaped missile configurations [1]. This tool includes mass budgeting, aerodynamics, and engine design according to user requirements, determined using analytical and semi-empirical methods. The user enters the properties of the subsystems themselves. The missile is divided into specific sections so that, missile aerodynamic parameters can be found. For each section, there are separate force and moment values, and a total missile aerodynamic characteristic is extracted by taking all the components.

The second one is a system design tool designed by Georgia Tech's Aerospace System Design Laboratory (ASDL) [2]. It is used for hypersonic missiles. Their aim is to create an integrated disciplinary code for conceptual sizing.  In ASDL, a request of proposal that is used for the basis for customer requirements for the design, a concept space for propulsion section and a modeling and simulation part is developed.

The third one is EXCON which is developed in 2009 [2]. It is used for optimizing the external configuration for subsonic cruise missiles. It can design two different cruise missile missions, including surface to surface and air to air missiles. A genetic algorithm is used for the optimization and a 2-Degree of Freedom (2-DOF) simulation is used for the analysis.

The fourth one is, Strategic Weapon Optimization for Rapid Design (SWORD) is developed by The Missile System Division (MSD) of Lockheed Missile & Space Co. Inc. (LMSC). It has been worked on this issue for more than 30 years. An attempt is made to create a design tool that optimizes both design and trajectory. Sword is used for conceptual design, to generate solid rocket designs and optimize its flight profiles [3].

Lastly, there also exist some options for aircraft designer such as FLOPS which performs the aerodynamic and propulsion design. After that, it makes a trajectory analysis to size a vehicle. However, these programs are not used for rocket or missile design studies.

Besides these tools, in the literature, a couple of studies about design and optimization methods have occurred.

One of them is held in 2000, focuses on the fact that the Genetic Algorithm has a capability for determination of high efficiency missile external geometry and robust missile aerodynamic design with respect to design goals and constraints [4]. In recent years, designers applied gradient based optimization algorithms to aerodynamic designs, but these methods are not suitable for undesirable restrictions [5]. Gradient based optimizer should be started with a specified set of initial parameters due to the bias of future solutions toward a local optimum. On the other hand, gradient based optimizers work efficiently if there is a small number of design variable and these variables are independent of each other. When the number of design variables increases and the coupling of the variables occur, gradient based algorithms do not have the capability to solve accurately [4]. In this study for aerodynamic prediction, AeroDesign is used. AeroDesign is developed at the U.S Army Aviation and Missile Command. AeroDesign is an empirically based package which is based on British wind-tunnel test data for numerous configurations. In the same study, it is suggested that AeroDesign can be replaced by a more robust code like Missile Datcom [6]. Moreover, as a result, it is said that the genetic algorithm has a capability of designing aerodynamic shapes and its performance is well in both single or multiple goal applications.

In addition, it has been observed in 2010 that Yang Young-Rok, Jung Sung-Ki, Cho Tae-Hwan, and Myong Rho-Shin optimize trajectory for increasing the range of rocket and missile systems [7]. It has been pointed out that the range can be increased by adding a gliding phase to the systems. It also focuses on the fact that control surface design has a big influence even on uncontrolled rocket system range.

Design optimization of aircraft integrates several disciplines, such as aerodynamics, structures, dynamics, controls, and propulsion. For multidisciplinary design, calculus-based methods, response surface methods, simulated annealing, neural networks, genetic algorithms, and combinations of them can be used. Calculus and gradient based methods are likely studied in the literature. And it should be added that these methods usually converge to a local minimum. However genetic algorithms and simulated annealing methods are most promising ones [8]. In the study of Tekinalp and Bingöl two formulations for maximum range trajectory optimization, total flight time and total energy approaches, are compared. It is demonstrated that the total energy approach, where the nodes after burnout are equally spaced in energy consumption, gives superior results. Hide-and-seek is also suitable for the combined optimization of design and control variables. The first aerospace application of hide and seek simulated annealing was applied by Lu and Khan in 1994 [9]. In that study, a maneuvering aircraft is used to find optimum trajectories. Moreover, it is seen that there exists a study about missile design and trajectory optimization is conducted with the same methodology [10]. Their aim is to create a new approach to the hide and seek method for the combination of missile design and trajectory optimization.

There exists a study about optimization of liquid propellant missile systems [11]. It is focused on modeling and optimization of a liquid propellant rocket engine, and it is created a series of codes to simulate the performance. Genetic algorithm is used for optimization. At the beginning of the optimization, defined boundaries are used and the required range is given. For aerodynamic calculation of the missile, Aerodsn is used. This tool is a kind of fast aerodynamic prediction tool and it is developed by U.S. Army Missile Command in 1980s [12]. Mass and inertia properties are found with a comprehensive analysis such that all the missile's components mass and inertia values are calculated one by one. Six degrees of freedom model is used for motion of the missile. The missile is assumed as rigid and all masses are stationary. The 6-DOF is used 7th-8th order Runge-Kutta numerical integration routine for simulation of the missile flight. The methodology can be used for both preliminary design and reverse engineering of liquid propelled missiles.

Historically, the design and performance optimization of guided, gun-launched projectiles is a difficult task for the designers due to the flight behavior and complex aerodynamic characteristics. Usually, constraints are also difficult to solve. In a paper, which held in 2015 by Fewler and Rogers [13], it is presented an alternative methodology for smart weapons conceptual designs and optimization based on design of experiments. In the beginning, basic aerodynamic shape and associated design parameters are given by the designer. Based on design of experiments, a kriging response surface is generated for performance criteria. Simultaneously neural network is trained to recognize the unstable designs in the design space. After that, genetic algorithm is used to define the optimum projectile design. The suggested method starts with Latin Hypercube DOE, continues with Kriging Model [14] and neural network classifier and ends with genetic algorithm optimizer [15].

It is conducted by Holst [16], that the reliability and success of gradient methods requires a smooth design space and only a single global optimum point. Moreover, for these methods to ensure the proper convergence, initial guess should be close enough to the global optimum. However, in constraints to gradient based optimization methods, design space search algorithms such as genetic algorithm offer an alternative approach, and these provide attractive features. The basic idea in the evolutionary algorithms is to search for optimum solutions using an analogy to the theory of evolution. Moreover, genetic algorithm can be used for multi objective or multi discipline optimization such that two or more objectives are simultaneously and independently optimized. In that study, genetic algorithm is used for two problems. The first one is a transonic wing maximization of the lift to drag ratio with the simultaneous minimization of structural mass and the second one is a transonic wing fuselage lift to drag ratio maximization with the simultaneous maximization of vehicle volume. For both cases, genetic algorithm converged.

In 2009, there exists a study about unmanned combat aerial vehicles (UCAV). Designer makes a study about multidisciplinary and multi objective design and optimization for UCAV. It is focused on the fact that in order to get the best results, which meets the requirements, some optimization techniques must be used to find an optimized aircraft combination [17]. In the optimization part, as a first step, it is implemented single objective optimization. For this aim, six objectives are chosen. A Fortran code is used for each of them. As a second step, it is focused on two objectives optimization. Some objective pairs are created and optimized. As a third step, three conflicting objectives are chosen and multi objective simulated optimization methods are used. As a result, it is said that the multi objective optimizations can be effectively used in aerospace applications.

When more detailed literature survey is conducted for the use of the genetic algorithm in aerospace engineering applications, many different studies is seen. One of them is about the wind turbines such as aerodynamic design and optimization of horizontal axis wind turbines, is done in 2018 [18]. The other one is optimization of types, numbers, and locations of sensors and actuators used in the model analysis of aircraft structures using genetic algorithm are held in 2017 [19]. Also, trajectory optimization of a tactical missile by using genetic algorithm is done in 2018 [20].

### 1.2.1 Conceptual Design of the Missiles

Conceptual design defines what a product is, how it can be used and what it can do. Moreover, it describes how the new product will meet the requirements at the beginning of a system design process. The results of the conceptual design studies are input for a more detailed design step. For complex systems such as missiles, it is required to make some appropriate concessions at the beginning of the design, in order to achieve a balance according to coupled objectives which are defined in terms of range, maneuverability, velocity, production cost and time. Usually, this is very difficult, and the system design process can be ended with an inefficient final design. Since a set of complex relations exist between requirements, constraints and time to improve the outcomes of the conceptual design studies, a multidisciplinary design should be made.

There exist complex interrelations between aerodynamics, propulsion, mechanical and trajectory design steps. Eugene L. Fleeman states that there exist several important major tasks of conceptual design. As it can be seen as Figure 1.1, the first step of any conceptual design starts with mission requirements definition, it continues establishing a baseline, aerodynamic design, propulsion design, and mechanical design, and so on [21]. As a last step, design engineer should ask whether the design meets the optimum performance parameters or not.

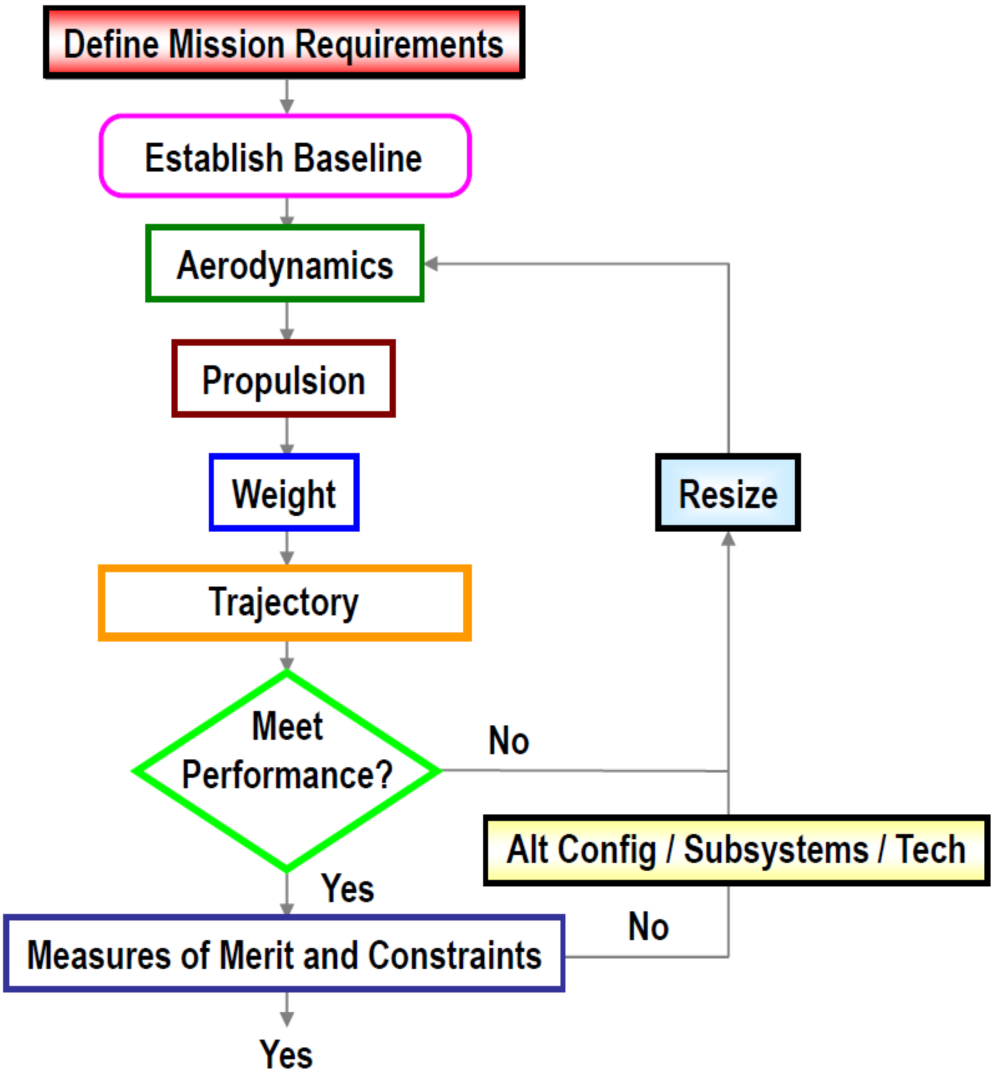



Figure 1.1: Design Iteration Map for a Missile [21]

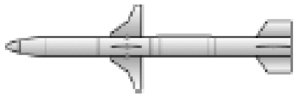
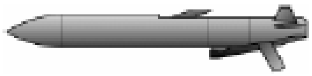
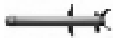
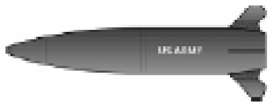
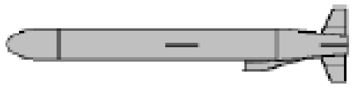
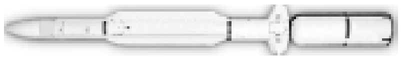
Conceptual design of a missile system is an iterative process. The initial process begins with the requirements that are determined by the customer of the product. Design variables that affect aerodynamic, propulsion and mechanical design are changed iteratively to meet the requirements. At that point, aerodynamic system design has a priority over other design phases because defining a configuration which is optimized in terms of aerodynamic performance reduces iteration number and so it decreases the time spent on the design process.

There also exist several major tasks of conceptual design which mission definition, weapon requirements, weapon concept design synthesis, and integration of the missile/rocket with the launch platform and development technology road map. These steps are in an iteration cycle to the end of the system design process.

### 1.2.2 Classification of Missiles

A powered, unguided munition is known as a rocket, a missile can be defined as an intelligent unmanned rocket which is designed to carry the payload to the designated point. Both rocket and missile systems are usually used to destroying the target [22]. Missiles can be classified according to their launch platform, target location, trajectory, range, and propulsion system and control type. According to launch platform and target location they can be classified as surface to surface, air to surface, surface to air and air to air missiles. According to trajectories, the most common ones are ballistic, cruise, anti-ship, and anti-tank missiles. According to ranges; there exist short, medium, intermediate and intercontinental missiles. Solid propulsion, liquid propulsion, hybrid propulsion, and scramjet are some of the examples of propulsion types. And last but least classification is according to their control types such as canard control, wing control and tail control. Table 1.1 shows some of the examples of missiles classification with respect to range and launch platform.

Table 1.1: Examples of Missiles According to Launch Platforms and Ranges [2]

| Launch Type | Missile Name | Geometry |
|---|---|---|
| Air to Air | Short range ATA. AA-11. |  |
| | Medium range ATA. AIM-120 |  |
| | Long Range ATA. Meteor |  |
| Air to Surface | Short range ATS. AGM-114. |  |
| | Medium range ATS. AGM-88. |  |
| | Long range ATS. Storm Shadow |  |
| Surface to Surface | Short range STS. Javelin. |  |
| | Medium range STS. MGM-140. |  |
| | Long range STS. BGM-109. |  |
| Surface to Air | Short range STA. FIM-92. |  |
| | Medium range STA. PAC-3. |  |
| | Long range STA. SM-3. |  |

One of the important classifications can be made based on the control type. Except for unconventional control systems such as thrust vector control, missiles are controlled with the help of aerodynamic lifting surfaces. Aerodynamic performance parameters and external geometry of the missile is strongly affected by the control surface location. Mainly, there exist three types of alternatives which are canard controlled, wing controlled and tail-controlled missiles. In Figure 1.2 control type alternatives are given. Each control type alternative has some advantages and disadvantages.

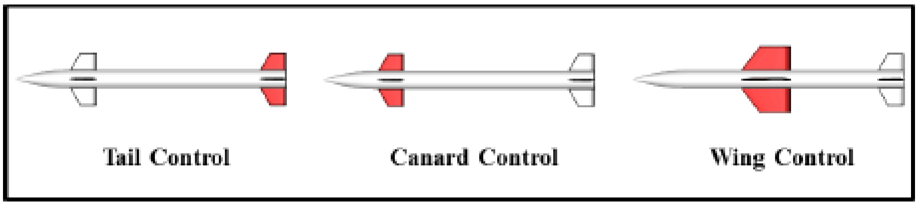
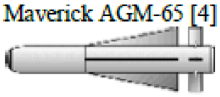
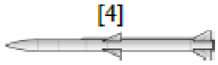
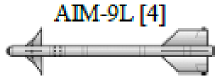
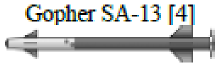
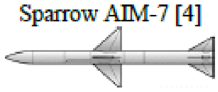
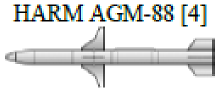



Figure 1.2: Control Type Alternatives for Missiles [7]

In Table 1.2 advantages and disadvantages of the control type alternatives are summarized. When selecting the control type properties, these should be considered because of the fact that this is also important for the mechanical properties and algorithm design.

Table 1.2: Control Type Alternatives and Their Properties [23]

| Control Type | Advantages | Disadvantages | Examples |
|---|---|---|---|
| Tail Control | • Efficient packaging<br>• Low actuator torque<br>• Low induced rolling moment<br>• Efficient at high angles of attack | • Decreased lift at low angles of attack | Maverick AGM-65 [4]<br><br>AMRAAM AIM-120 [4]<br> |
| Canard Control | • Efficient packaging<br>• Simplified manufacturing<br>• Increased lift at low angles of attack | • Stall at high angles of attack<br>• High induced roll | AIM-9L [4]<br><br>Gopher SA-13 [4]<br> |
| Wing Control | • Fast response<br>• Maneuverability at low angles of attack<br>• Small trim angle | • Poor packaging<br>• High hinge moments<br>• Large wing size<br>• Large induced roll | Sparrow AIM-7 [4]<br><br>HARM AGM-88 [4]<br> |

## 1.3 Objective of the Thesis

The objective of this thesis is to develop a tool which is used for the conceptual design studies of missile design, optimization and performance analysis of ballistic missile systems. The aim is to find the best possible system design in the design space with respect to performance parameters, cost and time issues. So, for this aim, a software tool is created for designing an external geometry optimization tool for surface to surface ballistic missile systems. With the help of this tool, the performance parameters are optimized in the conceptual design.

Missile design is a complex, time consuming and iterative process. One of the main purposes of designing this tool is to minimize the time spent during the conceptual design stage of the missiles. Ballistic Missile Optimization Tool (BMOT) should have three main components. These are aerodynamic design part, optimization part and performance analysis part. The aerodynamic design is required to be done according to requirements. Since a large design space can be created, they should be eliminated with respect to design constraints. For each design alternative, aerodynamic coefficient and required parameters for the optimization part are found. As a last step for performance analysis, a simulation is created. The required information for the simulation part is found with the help of the first two parts.

By using this tool in conceptual design studies, external geometry is created for surface to surface, short range, ballistic missiles. Process starts with by performing a similar system search in order to define the mechanical limits which can be called as inputs for the tool. After that, the second step aerodynamic system design process is started, and external geometry is found. Aerodynamic coefficients are created using Missile Datcom Software for each design alternative and these alternatives are tried to optimize with the help of Genetic Algorithm. Aerodynamic design process continues until the optimum geometry is found.

Numerous alternative configurations are rapidly eliminated with respect to constraints. The configuration, which has the best fitness value, is selected and tested with three degrees of freedom (3-DOF) simulation created in Matlab/Simulink software. In order to get faster results in the conceptual design phase, a 3-DOF model is used instead of six degrees of freedom (6-DOF) model. If the performance parameters satisfy, the conceptual design process stops, otherwise the design starts again from the first step.

## 1.4 Contribution of the Thesis

In today's world, system design works need to be updated so that fast solutions can be obtained instead of long-lasting system design cycles. Different design methods that are already used in other sectors are being integrated into missile system design to accelerate processes.

In order to keep up with technology and compete with other companies, it is very important to be able to design agile and produce fast designs. The more quickly the inputs required for preliminary system design work can be obtained, the more agile the system design process can be. Therefore, it has been prioritized to accelerate conceptual design studies that provide preliminary design information.

A Multidisciplinary optimization and performance analysis tool will be studied in this thesis. The aim is to create a system design tool for ballistic missiles that performs design, optimization and performance analysis in it. With the help of this tool, it can be achieved more agile system design process. For this aim, fast prediction tools are used. As an optimization method Genetic Algorithm, which is based on evolution theory, is chosen.

When the literature is examined, it is observed that the optimization studies for external geometry had been done in the missiles before. For these studies, it is seen that fast estimation tools are used in this study. However, no study has been found that performs system design, optimization, and performance analysis altogether and in which these variables can be parametrically changed by the user. As well as changing the reference parameters that shape the design, the user can quickly evaluate the results of the design while the subsystem data that directly affect the performance.

Compared to other studies, agility is considered in detail. Fleeman says that 'Be Agile to Survive in the Food Chain' to emphasize the importance of agility [24]. Since one of the main objectives of this system design tool is to speed up the conceptual system design process, alternative scenarios have been created to reduce computational time.

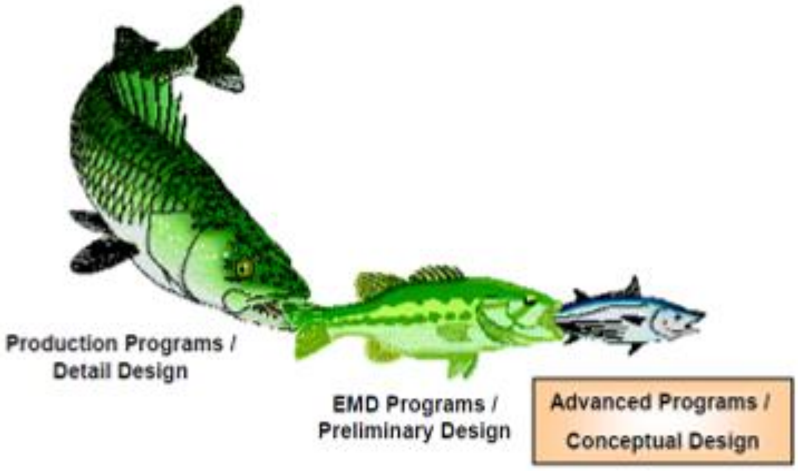



Figure 1.3: Be Agile to Survive in the Food Chain [24]

## 1.5 Scope of the Thesis

In Chapter 1, introduction to the problem, literature survey, objective of the thesis, contribution of thesis, and scope of the thesis sections are given. Background information, definition, and importance of conceptual design studies and detail information about missiles are mentioned. The steps of created tool are briefly defined.

In Chapter 2, aerodynamic design of the missiles, which is the first step of the created tool, is given. The start points of the process, competitor study phase and external geometry design with the help of Missile Datcom Software are investigated in depth. The required parameters and their definitions are given.

In Chapter 3, optimization part that is the second step is the BMOT is given. As mentioned above, in this study genetic algorithm is used. What is genetic algorithm; the subsections of genetic algorithm are defined one by one. Also, the comparison of genetic algorithm and one of the sequential quadratic programming methods are given.

In Chapter 4, the third step of the BMOT, simulation section is given. The details of simulations, the required information, estimated equations, equations of motions and assumptions are mentioned.

In Chapter 5, different case studies are conducted. In the first case study, two different optimization methods are compared. In the second case study, whole design process of BMOT is explained in detail. The third case study is related to the optimization loop details such as effects of the chromosome number and generation number on the optimization result and computational time. In addition, for agility, it is focused on to optimize the computational time by creating different scenarios. The last case study is directly related to optimization results for different objective functions. Also, it is focused on the comparison of their results. The alternative designs configurations mechanical properties and performance parameters are compared.

Finally, in Chapter 6, results, discussion, and possible future works are mentioned.

# CHAPTER 2

# AERODYNAMIC DESIGN OF MISSILES

## 2.1 Competitor Study

The conceptual design phase usually starts with the identification of the mission or operational condition needed and it continues with the definition of requirements or design of new technology products.

One of the most important goals of the conceptual design phase of a missile is to generate baseline geometry for a given mission. Initial baseline geometry is obtained according to requirements and using this geometry design cycle is started. In the conceptual design studies, parametric trade off studies is performed to establish a system or component constraints.

In BMOT, as a first step user should make a similar system competitor study. The other products properties are examined. Products geometrical properties and performance parameters such as range and velocity are analyzed. After that, the most suitable one is selected as reference missile properties. The second step is the aerodynamic design part. To start aerodynamic design, the external geometry properties should be defined.

In this study, the surface to surface ballistic missile systems are considered. Usually, ballistic missiles have tail or canard controlled. According to the control type, their fin set properties are changed. Ballistic performance of a missile is strongly dependent on the external geometry of the missile. The nose shape, nose length, fin configuration, fin set locations should be optimized. When these parameters are optimized, the performance is also optimized too. The third step is optimization. The last but not least step is the performance analysis part.

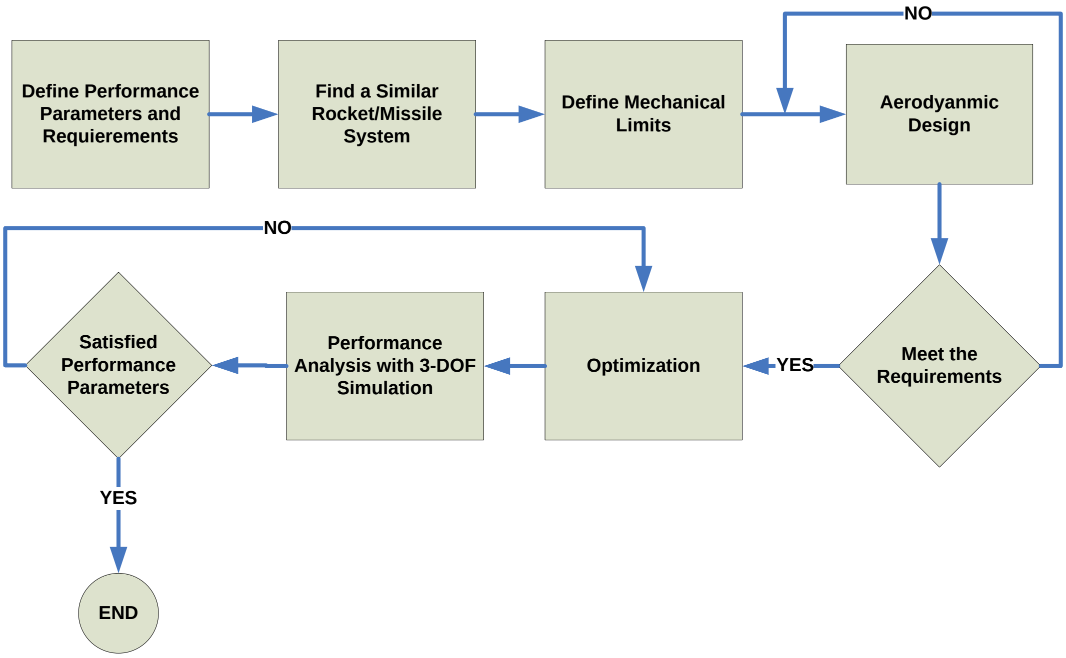



Figure 2.1: BMOT Design Steps

BMOT design steps are given in Figure 2.1. As a first step, system requirements are defined, and external geometries are designed according to these requirements. Aerodynamic coefficients are required to be found for each design configuration alternative. Since there are many different geometry solutions, they should be evaluated according to performance results. This procedure should be very fast considering the total run time. For this purpose, in this study Missile Datcom [25] and Matlab/Simulink Software are used. Aerodynamic coefficients are found with the help of Missile Datcom and 3 Degrees of Freedom (3-DOF) Simulation model are created with Matlab/Simulink. Both software are appropriate for rapid design configuration. The alternative designs are created, aerodynamic parameters are found and the Genetic Algorithm is used for optimization. Optimized designs are selected and tested with the help of simulation. The other alternatives are eliminated. So, the best alternative is found.

## 2.2 External Geometry Design with Missile Datcom

When designing a missile external configuration, the most important performance parameters are range, velocity, control effectiveness, and maneuverability. It is seen that the range and velocity are strongly dependent on the mass, lift force and dynamic pressure. Maneuverability is related to the control effectiveness, the force which acts on the missile geometry, pitching moment and inertia.

In order to find the best configuration, different fin configurations such as number of fin sets, fin sets locations, and fin's geometrical properties, different control type alternatives (canard control or tail control), nose shapes are studied. For every fin sets; root chord, tip chord, span, locations are tried to be optimized. It should be stated that there exist some constraints like static and dynamic stability of the missile, controllability and mechanical properties.

To start aerodynamic design, the external geometry properties should be defined. In this study, the surface to surface ballistic missile systems are considered. Usually, ballistic missiles have tail or canard controlled. According to the control type, their fin set properties are changed. BMOT can be used for both canard and tail-controlled missiles. BMOT needs 11 parameters for tail-controlled missiles, 21 parameters for canard-controlled missiles.

There exists some important parameters for missile external geometry design such as, longitudinal reference length (LREF), reference area (SREF), nose length (LNOSE), nose diameter (DNOSE), nose bluntness ratio (BNOSE), type of nose shape (TNOSE), center body length (LCENTR), center body diameter at base (DCENTR), nozzle diameter (DEXIT), longitudinal coordinate of nose tip (X0), longitudinal center of gravity for data (XCG), semi span locations for each fin set (SSPAN), sweepback angle at each span location (SWEEP), distance from missile nose to chord leading edge at each span location (XLE), chord station used in measuring sweep (STA), number of each panels in fin set (NPANEL), roll angle of each fin measured from top vertical center (PHIF), thickness to chord ratio of upper surface for each span location (ZUPPER), thickness to chord ratio of lower surface for each span locations (ZLOWER), fraction of chord from leading edge to maximum thickness of upper surface for each span location (LMAXU), fraction of chord from leading edge to maximum thickness of lower surface for each span location (LMAXL), fraction of chord of constant thickness section of upper surface for each span location (LFLATU),  fraction of chord of constant thickness section of lower surface for each span location (LFLATL). Figure 2.2 shows the representation of the required parameters.

Fin configuration is very important for missile external geometry design studies. Its number and placement on the missile body effects the missile performance. Fins are called as canard, wing or tail according to their place on the main body. A canard can be defined as the small control surface, which is in the front section of the missile whereas tail is located in the rear section of the missile body. The wing is usually larger than the canard and located in the mid-section of the missile body. The number of each fin set is also not constants. There exist so many alternative configurations and the number of panels can be two, three, four, six and eighth such as 2 wings and 4 tails (024), 4 wings and 4 tails (044), 4 canards and 4 tails (404), etc. Fin configuration is also important for control effectiveness of the missiles. In this study, 4 canards and 4 tails configurations are examined because in ballistic missile system design process usually canard and tail controlled are preferred.

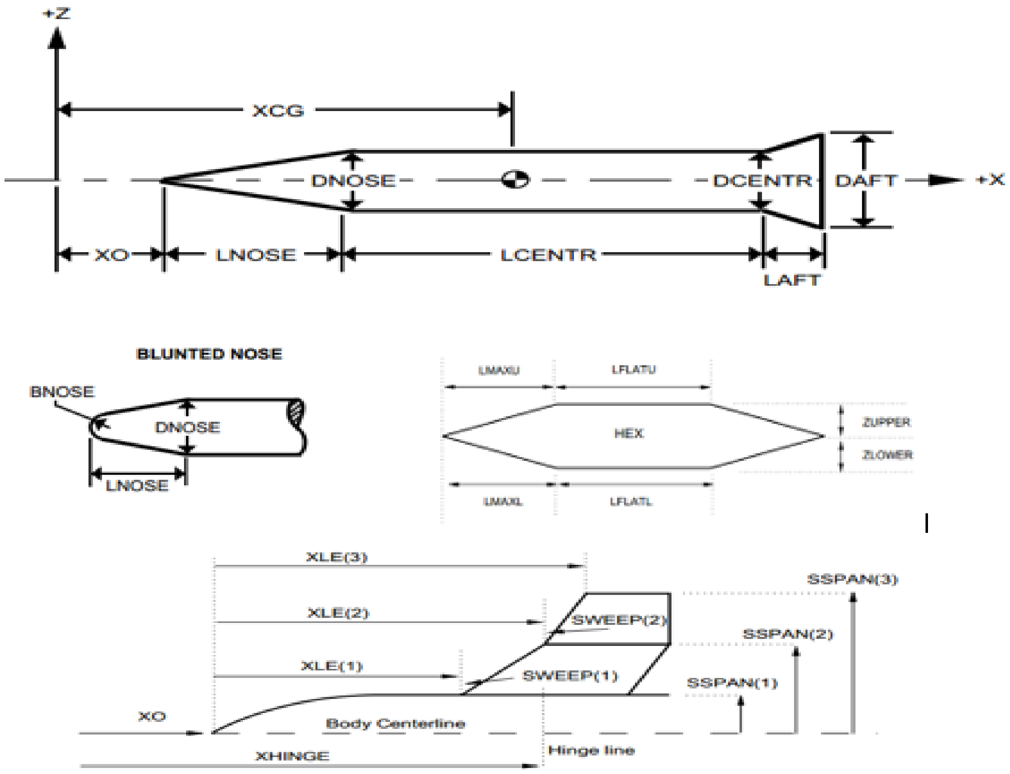



Figure 2.2: Definition of Required Parameters [25]

The wing control is not selected in recent years due to large induced roll effects and large hinge moment needs.

The orientation of fin surfaces is also one of the important factors for fin set design. There exits two different alternative orientation. These are plus and cross. For both cases, fin panels are perpendicular to each other.

## 2.3 Aerodynamic Forces and Moments

A missile motion can be defined with the help of six degrees of freedom (6-DOF) equations. Three aerodynamic forces and three aerodynamic moments are considered. To define the directions of these forces and moments reference coordinate frames are used. It should be noted that aerodynamic coefficients are found from these forces and moments. Forces divided by the free stream dynamic pressure and reference length of the missile (LREF) while the moment coefficients are calculated by dividing the moments with the free stream dynamic pressure (Q) and reference area (cross sectional area of the missile body). In Figure 2.3 schematic representation of longitudinal forces and moment on the missile, the body is given. In this study, to get faster results in the conceptual design phase, a 3-DOF model is used instead of a 6-DOF model.

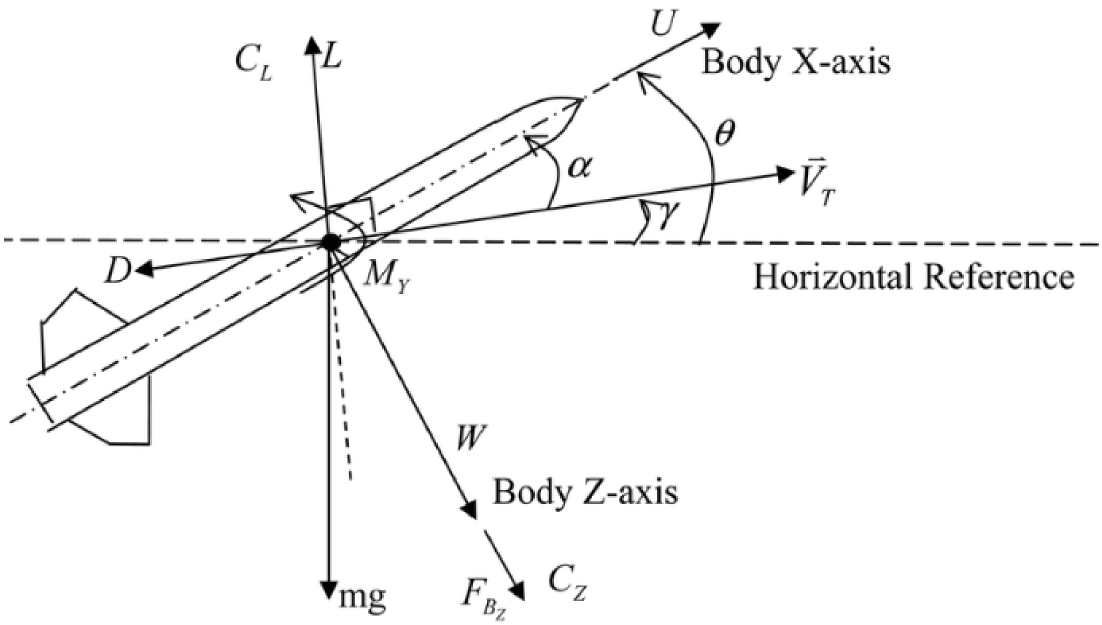



Figure 2.3: Longitudinal forces and moments acting on missile [26]

### 2.3.1 Aerodynamic Coefficients

Calculation of dynamic pressure, force and moment coefficients are given in Eqs. (2.1), (2.2), (2.3), and (2.4)**.** Axial force coefficient, in other words, drag coefficient ($C_x$), is positive in negative x direction whereas normal force coefficient ($C_N$) is positive in the negative z direction. Aerodynamic forces and moments are converted to non-dimensional coefficients.

$$q = \frac{1}{2}\rho_\infty V^2 \quad (2.1)$$

$$C_x = \frac{Axial\ Force}{qS_{ref}} \quad (2.2)$$

$$C_N = \frac{Normal\ Force}{qS_{ref}} \quad (2.3)$$

$$C_m = \frac{Pitching\ Moment}{qS_{ref}L_{ref}} \quad (2.4)$$

The required aerodynamic coefficients are found with the help of Missile Datcom software. In this study, 3-DOF model is used to define the motion of the missile. $C_x$ (Both for boost and coast phase), $C_N$ and $C_m$ coefficients are calculated.

### 2.3.2 Static Stability

One of the most important aerodynamic design parameters is the static stability. The static stability can be defined as the slope of the pitching moment ($C_m$) with respect to the angle of attack ($\alpha$). The stability definition of missile is given Figure **2.4**.

Stability has an impact on the external configuration design so much, especially in fin configuration design. If the missile is statically stable, when the angle of attack increases, negative pitching moment occurs, and the nose of the missile drives down. In order to have static stability in the pitch axes, the slope of the pitching moment coefficient with respect to the angle of attack ($C_{m_\alpha}$) should be negative. In Figure 2.5, static stability curve is given. It is seen that when the fin is deflected the curve moved.

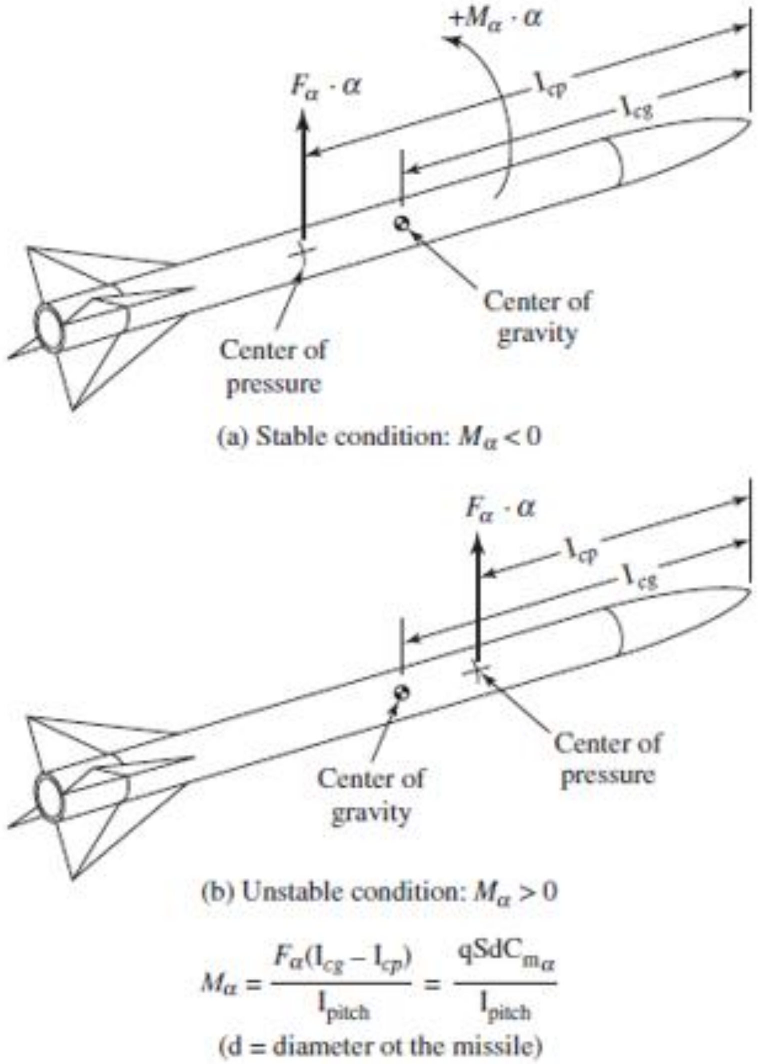



Figure 2.4: Aerodynamic missile stability definitions [27]

Without any deflection to the fins, the static stability curve passes through the origin for symmetric missiles. If the designer wants to operate the missile in a constant trim angle of attack, the restoring moment should be canceled out the moment, which is created by the fin deflections. Eq. (2.5) shows the calculation of static stability.

$$C_{m_a} = \frac{\Delta C_m}{\Delta \alpha} \leq 0 \tag{2.5}$$

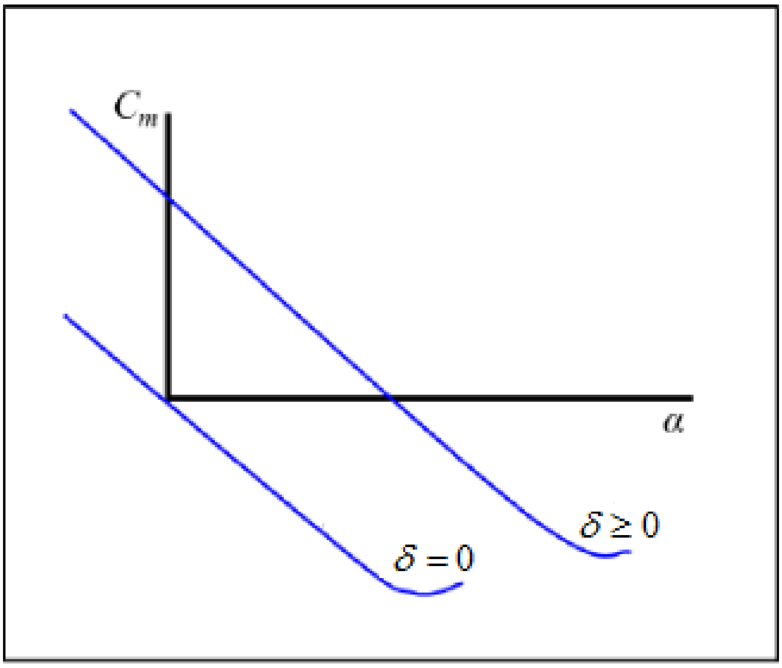



Figure 2.5: Static Stability ( $C_{m_\alpha}$ ) Curve

Another important term for the static stability is the static margin which can be defined as the distance between missile center of pressure ( $X_{CP}$ ) and center of gravity ( $X_{CG}$ ) divided by the missile diameter ( $d$ ). Figure 2.6 shows the static margin representation for stable missile configuration.

Eq. (2.6) summarizes the static margin calculation. If the static margin;

- Negative → stable missile configuration
- Zero → marginally stable missile configuration
- Positive → unstable missile configuration

$$SM = \frac{X_{CG} - X_{CP}}{d} \tag{2.6}$$

Smaller static margin values mean that a stable missile can be trimmed ($C_m = 0$) at a high angle of attacks and produce high normal force. Moreover, it has increased maneuverability [6].

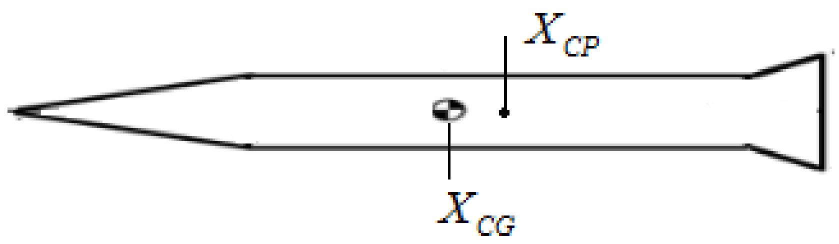



Figure 2.6: Static Margin Representation for Stable Missile Configuration

### 2.3.3 Control Effectiveness

Another important aerodynamic design parameter is the aerodynamic control effectiveness that can be defined as the ratio of the control surface deflection at trim condition to the angle of attack. Formulation of control effectiveness is given Eq. (2.7). It has a great influence on the canard and tail sizing. It can be also defined as the effect of the control surface deflections on the pitch, roll and yaw angles of the missile. It should be stated that for a missile; roll, yaw and pitch control effectiveness exist. They can be defined as;

- Roll due to → rudder, side slip, and roll angle
- Pitch due to → alpha
- Yaw due to → aileron and sideslip.

$$\text{Control Effectiveness} = \frac{\delta_{Trim}}{\alpha} \tag{2.7}$$

As mentioned before in this study, 3-DOF motion is considered. So, the only control effectiveness criteria come from the pitch due to alpha. The aerodynamic control effectiveness of missile roll and yaw axes are not considered.

In order to find the control effectiveness ratio is pitch due to alpha, the pitching moment coefficient derivative with respect to fin deflections and alpha can be used. Eq. (2.8) shows the relation between $C_{m_\delta}$ and $C_{m_\alpha}$ for controllability in pitch axes. If the missile has smaller control effectiveness, it can be trimmed at a higher angle of attack values. Also, it has better controllability and maneuverability [28]. Eq. (2.8) can be rewritten as Eq. (2.9). In order to have a controllable missile design Eq. (2.10) should be satisfied. Moreover, to calculate the control effectiveness; the required coefficients can be found with the help of Missile Datcom.

$$\frac{C_{m_\delta}}{C_{m_\alpha}} \leq 1 \tag{2.8}$$

$$\frac{C_{m_\delta}}{C_{m_\alpha}} = \frac{\Delta C_m}{\Delta \delta} \frac{\Delta \alpha}{\Delta C_m} = \frac{\Delta \alpha}{\Delta \delta} \tag{2.9}$$

$$\frac{\Delta \alpha}{\Delta \delta} \geq 1 \tag{2.10}$$

### 2.3.4 Maneuverability

Maneuverability can be defined as how fast the missile's maneuver occurs. It is also directly related to the normal force that acts on the missile geometry [2]. Maneuverability is very important;

- to overcome unexpected disturbances
- to follow required flight trajectory to reached to the target

It should be also stated that, in missile system design process, control effectiveness and maneuverability should be considered carefully. Because, control effectiveness shows the angle of attack, which is caused by fin deflections, while maneuverability is directly related to how fast this angle of attack change occurs.

Load factor is a measure for maneuverability of a missile. It can be calculated with the ratio of the normal force that is due to the aerodynamic force and gravitational force [28]. Formulation of load factor is given Eq. (2.11). Also Eq. (2.12) shows the calculation of normal force.

$$n = \frac{N / m}{g} \tag{2.11}$$

$$N = C_N \cdot S_{ref} (0,5 \cdot \rho \cdot V^2) \tag{2.12}$$

where,

N: Normal Force

$C_N$: Normal Force Coefficient

## 2.4 Constraints of External Geometry Optimization

While designing new external geometries, there exist some constraints that restrict the scope of the problem and determine the boundaries of design parameters. Some constraints can be due to launch platform limitations, and they can be taken into account in the determination of the maximum and minimum values. However, some constraints are directly related to performance such as stability and control effectiveness. In the aerodynamic design part, there exist two important constraints shown in Eq. (2.13) and Eq. (2.14).

$$C_{m_\alpha} \leq 0 \tag{2.13}$$

$$\frac{\Delta\alpha}{\Delta\delta} \geq 1 \tag{2.14}$$

In every iteration, constraints are checked for all dataset values. If the design provides constraints, its dataset goes to the next step. Otherwise, it is directly eliminated.

# CHAPTER 3

# OPTIMIZATION

## 3.1 Introduction

In this chapter, the optimization method, which is used in the conceptual design phase, is introduced. Two different optimization technique, such as sequential quadratic programming and genetic algorithm are studied.

Sequential quadratic programming (SQP) is a kind of iterative optimization method for constrained nonlinear optimization. This method can be used for mathematical problems that the constraints and objective functions are differentiable. SQP method has local convergence properties such that it will generate sequence of iterate to converge a local optimum solution [29]. It means this method is strongly dependent on the initial guess. In this study, fmincon which is an embedded Matlab function is used as an SQP method.

As a second optimization technique genetic algorithm is chosen. Genetic Algorithm is a global optimization method derived from biology itself. It is based on survival of the fittest individual as in nature. It is a type of optimization algorithm, to find the optimal solution for a given computational problem that maximizes or minimizes a particular function. In this method, evolutionary computation is taken as the mainstay, in that biological process of reproduction and natural selection is imitated to solve for the fittest solution. Like in evolution, many of a genetic algorithms process is random, however, this optimization technique allows one to set the level of randomization and the level of control [30]. The main components of the Genetic Algorithms are; a fitness function for optimization, a population of chromosomes, selection of which chromosomes will reproduce, crossover to produce next generation of chromosomes and the random mutation of chromosomes in new generations [31].

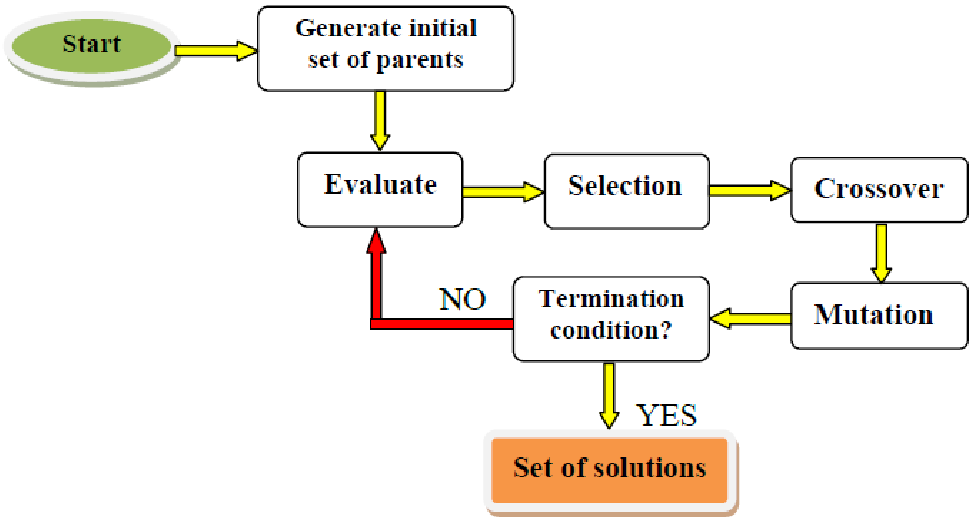



Figure 3.1: Genetic Algorithm Process

## 3.2 Genetic Algorithm

### 3.2.1 Fitness Function

Optimum solution of the desired problem is evaluated by the fitness function. By definition, a fitness function is a function such that the genetic algorithm is trying to optimize, in other words, it determines how to fit a solution is. In genetic algorithms, solution set or a population is represented by many chromosomes. Each chromosome has to be tested and it is come up with the best set of solutions to solve a given problem. Each solution, therefore, needs to be considered such that how close it meets the requirements of the desired solution.

In genetic algorithm, each design has its own fitness function. Identifying the fitness function for the genetic algorithm design may be the tough part so that when it is identified rest of the sections would be straightforward. There is no rule that a particular function should be used as a fitness function. It should be selected as the function which is maximizing or minimizing for the selected study.

### 3.2.2 Selection

One of the most significant sections of the genetic algorithm is selection. Its role is determining which individual genetic identity in the population will is passed on the next generation. The object of the selection is to reach the fittest individual, in other words, fittest solution.

One of the selection techniques of the genetic algorithm is that parents are selected randomly from the population by a technique called “roulette-wheel” selection [32]. In roulette-wheel selection which gets its name from the fact that algorithm works like a roulette-wheel, higher values have greater fitness. Main idea behind it is that good individuals will probably be selected more than poor ones. Like in roulette-wheel itself, in this method, each slot is paired with an individual in the population. Size of each slot determines with the fitness function such that if the value of fitness function is higher, size of the slot is proportionally bigger than others. Negative values are not allowed because that, there is no way to allocate a slot for a negative size. If any negative values are encountered, these values are converting to positive ones by adding some constant value.

Roulette wheel selection is taken as;

- Sum up all the fitness values in the current population
- Divide each individual's fitness value to the sum of all the fitness values to get the normalized fitness values.

- Sort the normalized fitness values
- Generate a random number between 0 and 1
- Subtract each individual's normalized fitness values to each other step by step with starting to one with descending order, and check whether the generated random number is higher or not.
- When generated random number has a higher value, select the last subtracted individual as one of the parents.
- Do the same thing to select other parent.

Roulette-wheel selection may not be always fair, because of random error or known as stochastic errors. However, an important part of all legitimate genetic algorithm techniques is to put forward fitter individuals and letting them reproduce more often. So, the roulette-wheel technique is done by weighting higher fitness values naturally.

### 3.2.3 Crossover

Third important part of genetic algorithm is crossover which is the process of exchanging genes between two chromosomes. This operator maintains diversity of chromosomes or in reality solutions. Two parents which are selected in the previous process, selection, combined to produce a new individual, or one can call this individual as a child. Reproduction of individuals is continued until the new population is reached same amount of people with respect to old population. One key point about the crossover, all new individuals may not be produced through children. In genetic algorithm crossover process, there might be a chance same parents maintain through generation. This ratio is called as probability of crossover.

Different crossover techniques may be applied in the genetic algorithm. All techniques are applicable to many types of problems, but some may need problem specific techniques. Some of crossover techniques are listed below. The list is not included all crossover techniques, but some significant ones at literature.

- Single – Point Crossover
- Multi – Point Crossover
- Uniform Crossover

#### 3.2.3.1 Single-Point Crossover

In this method, randomly selected point is used as a cut point. Each point has an equal chance to be selected. Steps for Single-Point crossover can be described as;

- Randomly, select a point between any two genes
- Copy first subpart of parent 1 and second subpart of parent 2 to the child 1
- Copy first subpart of parent 2 and second subpart of parent 1 to the child 2
- Generate two random number
- If the first random number is less than the probability of crossover then first new individual is child 1, otherwise, it is parent 1
- If the second random number is less than the probability of crossover then the second new individual is child 2, otherwise, it is parent 2

As an example of single point crossover is shown in Figure 3.2.

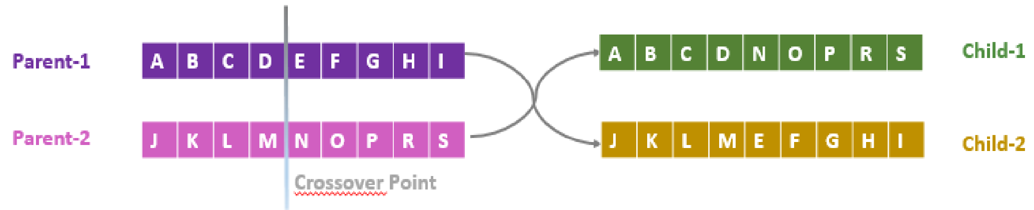



Figure 3.2: Single Point Crossover

Each crossover brings with two new individuals. It continues until it is reached the same amount of people with respect to old population.

#### 3.2.3.2 Multi -Point Crossover

Multi – point crossover is similar to the one point crossover with one major difference which is here, instead of one cut point, there are two or many cut points. These cut points are selected randomly and two offspring are generated from them such as;

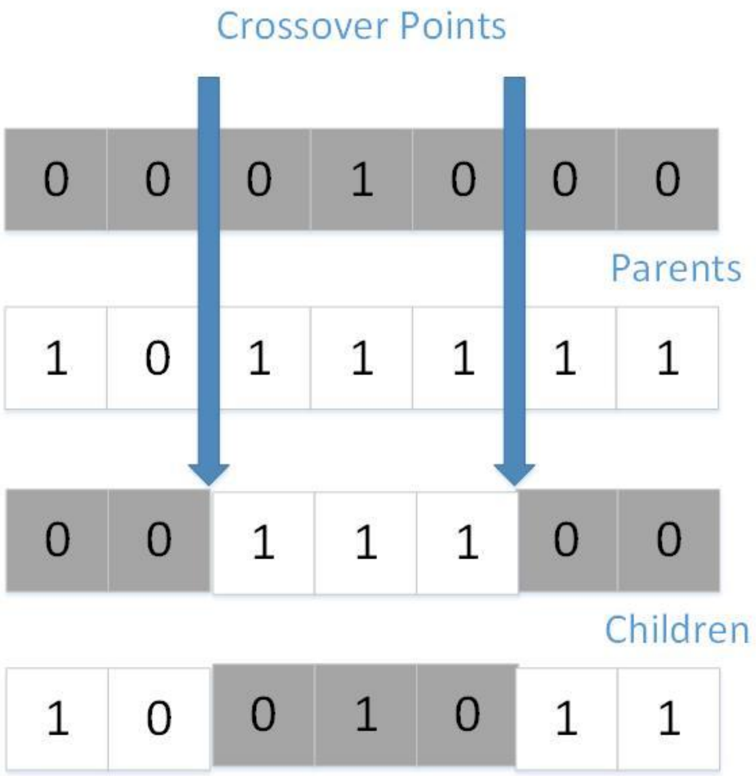



Figure 3.3: Multi Point Crossover

- Select k many cut points randomly between genes of each parent. Each parent's gene should be cut same points.
- Copy first, third and $(k+1)^{th}$ subpart of parent 1 and second and $(k)^{th}$ subpart of parent 2 to the child 1
- Copy first, third and $(k+1)^{th}$ subpart of parent 2 and second and $(k)^{th}$ subpart of parent 1 to the child 2
- Generate two random number

- If first random number is less than probability of crossover then first new individual is child 1, otherwise it is parent 1
- If second random number is less than probability of crossover then second new individual is child 2, otherwise it is parent 2

As an example of two point crossover is shown at Figure 3.3.

#### 3.2.3.3 Uniform Crossover

Different from other methods, in the uniform crossover, chromosomes are not divided into segments; rather each gene is treated separately. It is essentially like flip a coin for each gene of each chromosome whether the gene of offspring is come from parent 1 or parent 2.

- For offspring 1 generate a random number rather 0 or 1.
- If the random number is become TRUE, then gene of offspring 1 is come from parent 1, otherwise, it is come from parent 2.
- Repeat the procedure, until all genes of offspring 1 are completed.
- Remaining genes are assigned to offspring 2.

As an example, uniform crossover is shown in Figure 3.4.

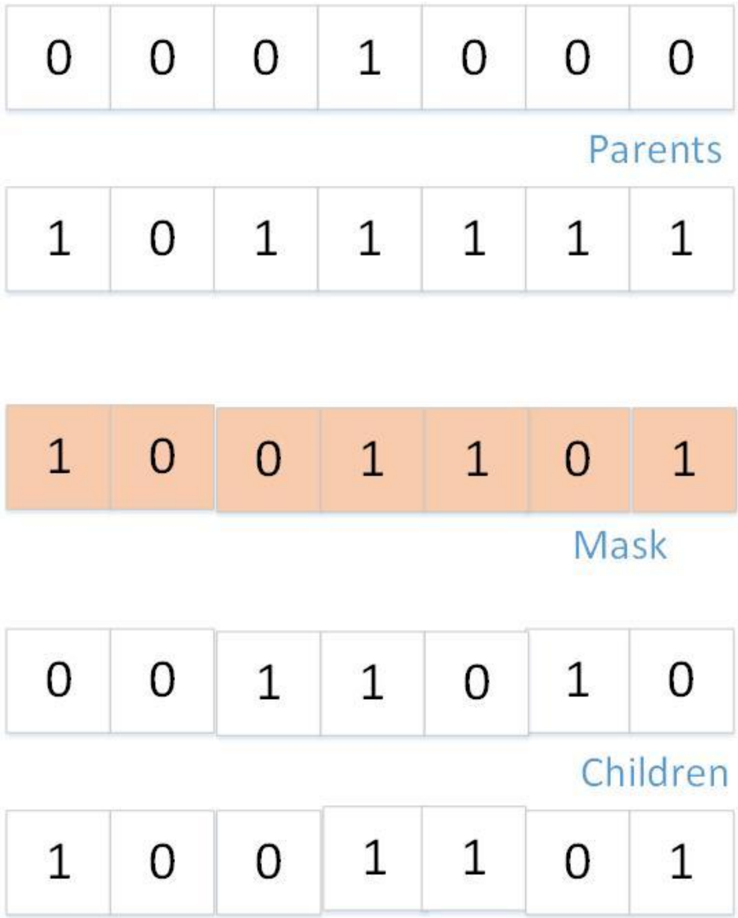



Figure 3.4: Uniform Crossover

### 3.2.4 Mutation

A new population full of individual is created after selection and crossover are completed. While some individuals are remaining same, others are produced by crossover. However, crossover operator is used for the search method of genetic algorithm. On the other hand, mutation is vital to keep diversity in the population. Effects of the mutation operator change one to zero with a small probability of mutation factor. Figure 3.5 shows how a string mutated to another string.

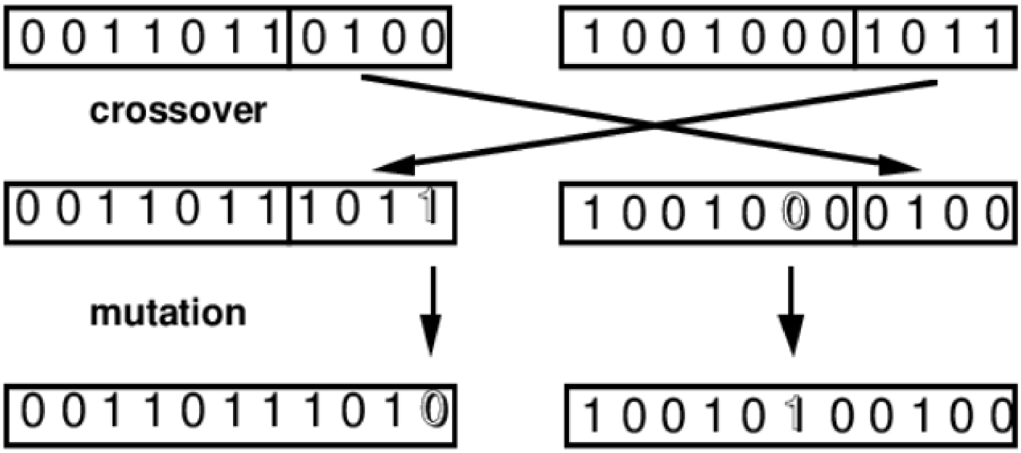



Figure 3.5: Mutation

### 3.2.5 Elitism

Elitism is not an essential process of Genetic Algorithm, but it is strongly recommended. It aims to preserve a number of the best individuals by generations so that they do not vanish from the population. It involves copying more convenient solutions to the next generation by a factor of elitism ratio. Because of the fact that appropriate solutions are copying to the next generation rather than reproduce, this method has a negative influence on population diversity. However, in relatively small size population, it helps to speed up to reach the optimum solution. In the end, it should be decided between quick results and diversity problems.

### 3.2.6 Comparison Between Matlab GA Tool and Designed GA Tool

In this study, Matlab GA Tool is also used to validate Designed GA Tool. GA Tool has a graphical user interface, embedded in Matlab, and the user only gives required information for optimization. General view of Matlab GA Tool is given in Figure 3.6 and Figure 3.7.

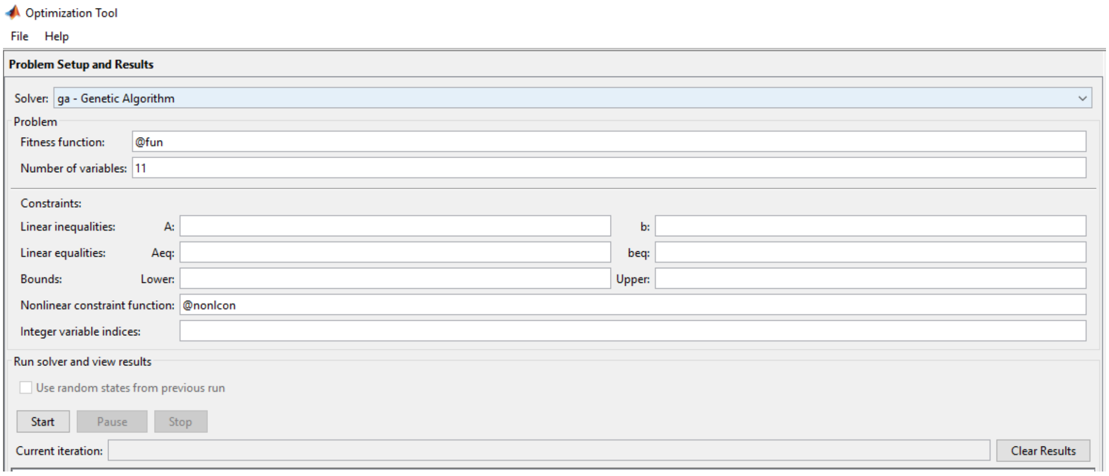



Figure 3.6: Problem Setup Matlab GA Tool

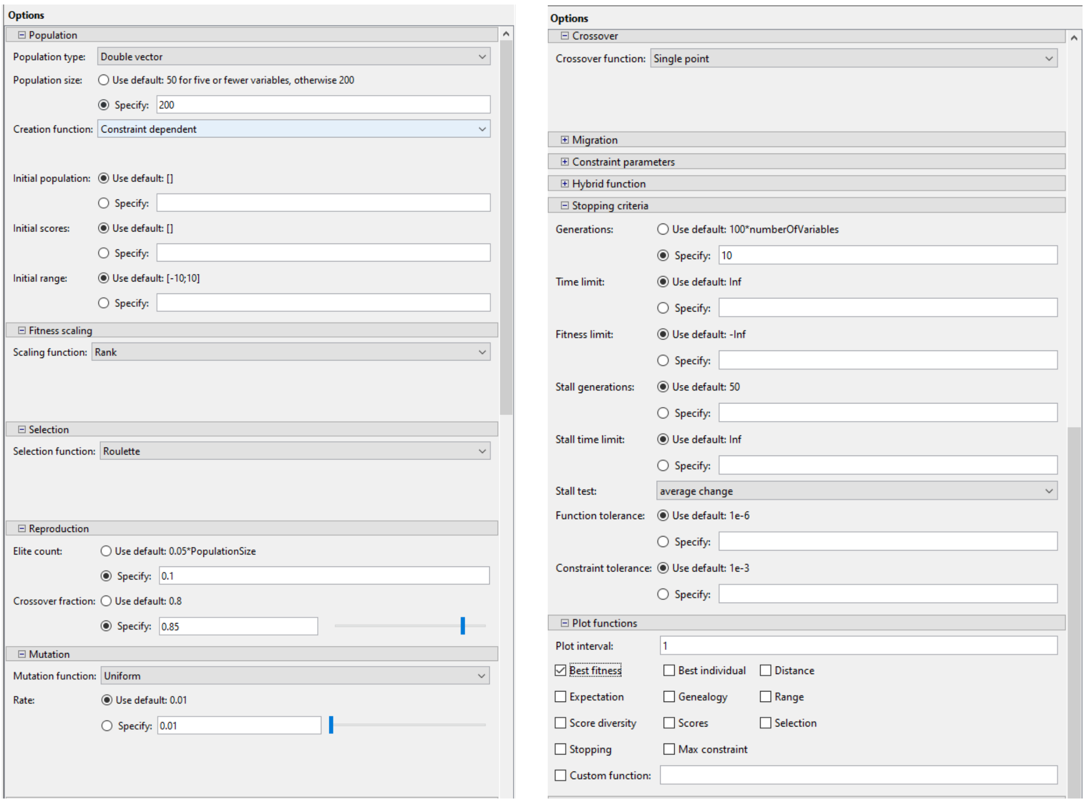



Figure 3.7: Options of Matlab GA Tool

Where fitness function and constraints are the same as the created GA tool. In options part, population size is changing with every case study, fitness scaling is chosen as rank, and selection type is chosen as roulette selection. Elite ratio is 0.1

and the probability of crossover, in other words, crossover fraction, is 0.85. Mutation is selected as uniform mutation with 0.1 probability of mutation ratio. Crossover type is selected as single-point crossover and stopping criteria is determined with generation number.

## 3.3 Sequential Quadratic Programming

Sequential Quadratic Programming method is one of the optimization algorithms for solving differentiable nonlinear equations. It can be gained detailed theoretical background by Stoer [33]. Also, Papalambros and Wilde [34] and Edgar and Himmelblau [35] are introduced more practical point of view about SQP. The basic idea is solving a quadratic programming subproblem in each iteration with linearizing constraint and approaching the Lagrangian function quadratically [36]. SQP subproblems should be constructed in a way that the resulting sequence of solutions converges to a local optimum of the nonlinear problem. [37]

In this study, fmincon, which is the one of SQP method to find a minimum of a constrained nonlinear multivariable function, is used. As mentioned above, for this optimization Matlab embedded function is used.  Starting an initial estimate, this function is trying to find local optimum with respect to constraints. Syntax of fmincon is given in Eq. (3.1) and constraints of fmincon are given in Eq. (3.2).

$$x = f\min con(fun, x0, A, b, Aeq, beq, lb, ub, nonlcon, options) \qquad (3.1)$$

$$\min f(x) \begin{Bmatrix} A \cdot x \le b \\ A_{eq} \cdot x = b_{eq} \\ lb \le x \le ub \\ c(x) \le 0 \\ c_{eq}(x) = 0 \end{Bmatrix} \qquad (3.2)$$

where;

$A$ and $b$ are coefficient of linear inequalities, $A_{eq}$ and $b_{eq}$ are coefficient of linear equalities, $lb$ is lower bound of design variables, $ub$ is upper bound of design variables. $c$ is coefficient of nonlinear inequalities and $c_{eq}$ is nonlinear equalities of fmincon. With $options$, many parameters can be controlled. Algorithm type is one of the controlled parameter by it. In this study, algorithm type is chosen as ‘sqp', while the default algorithm type for fmincon is ‘interior-point’.

# CHAPTER 4

# MODELLING AND SIMULATION

The output of the Genetic Algorithm is taken as the best alternative and this gene's aerodynamic coefficient database is calculated using Missile Datcom. As a last step, to examine the performance analysis 3-DOF Model is used. The model has capability to solve longitudinal equations of motion for any given missile geometry. The simulation consists of earth parameters, flight parameters, aerodynamics, mass and inertia, propulsion and equation of motions blocks. The inputs and outputs of each block are given in Figure 4.1.

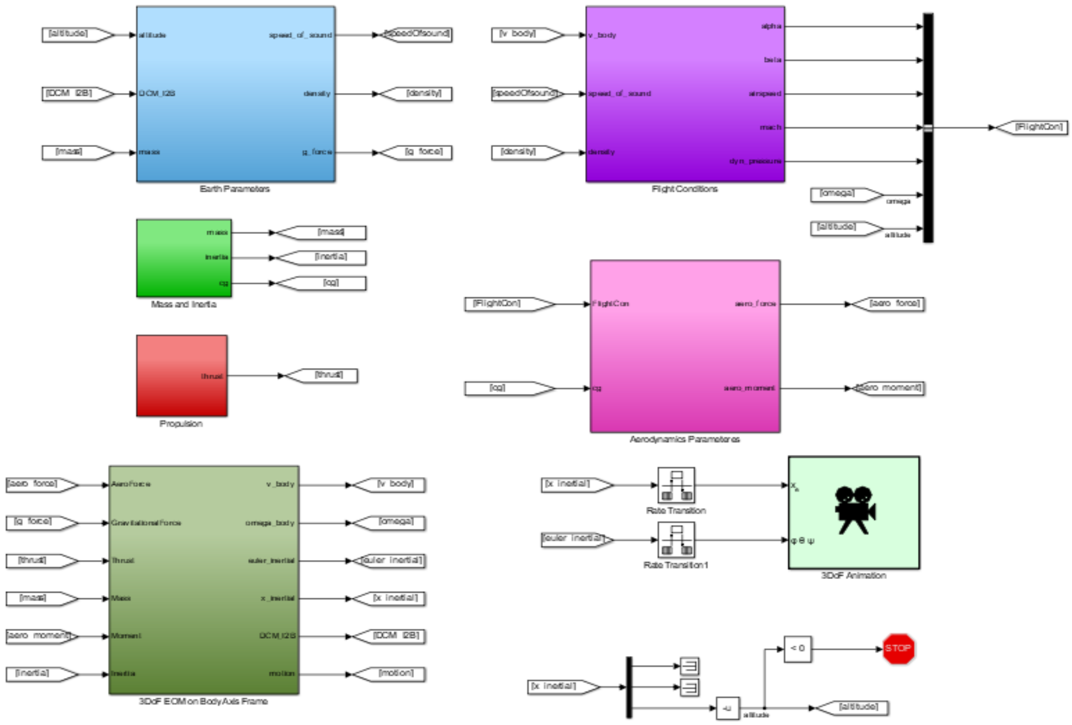


Figure 4.1: 3-DOF Model

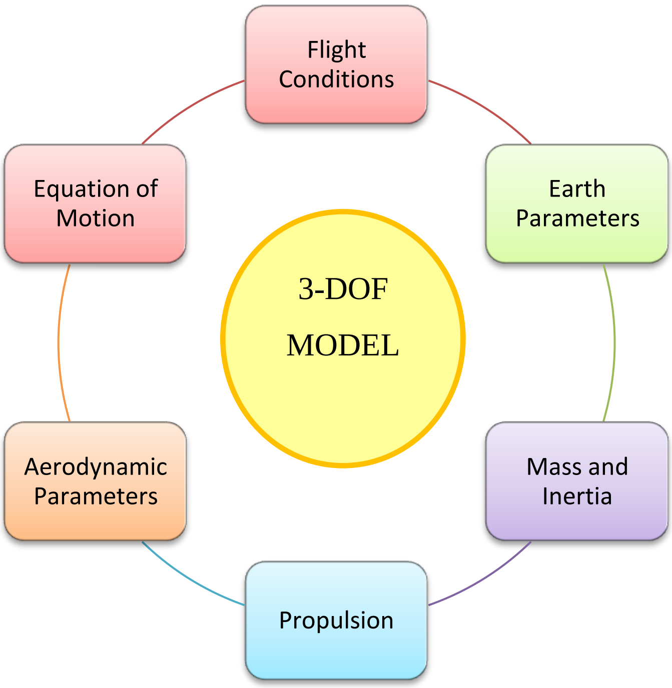



Figure 4.2: Schematic representation of 3-DOF Model

### 4.1 Equation of Motion Block

The equation of motion (EOM) block includes the dynamic calculations. It uses the all the forces, moments, mass and inertia values, which acts on the missile body, to calculate the required information to define the motion of the missile such as velocity and attitude (theta). In this block, also linear and angular positions of the missile are calculated.

To define the motion of the missile, two reference coordinate frames are used. The first one is the inertial (earth-fixed) reference frame and the second one is the body reference frame. Axes definitions of them are given in Figure 4.3. Gravity (g) changes with the altitude and always Z direction of the inertial reference frame. X and Y axes of the inertial reference frame obey non-rotating. The body reference frame is fixed to the missile. The origin of the body reference frame is coincident with the missile's center of gravity. $X_b$ axis toward to the nose of the missile while,

$Y_b$ towards to the right when the missile in $0^o$ roll position and $Z_b$ axis completes the right-hand rule.

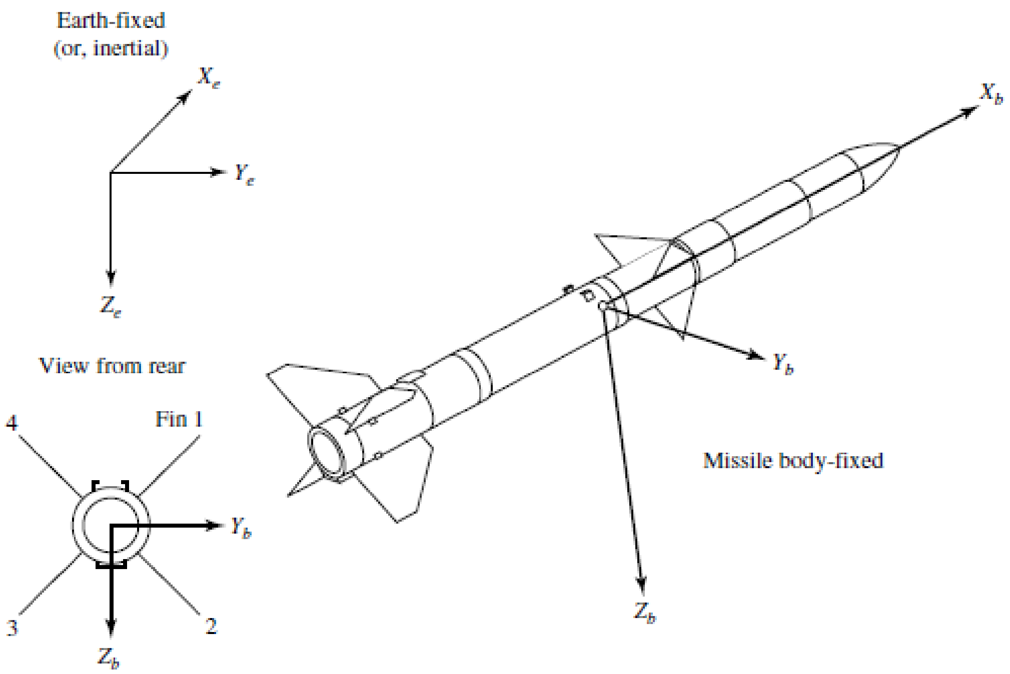



Figure 4.3: Missile Body and Inertia Axes Definitions [27]

As mentioned above, in this study 3-DOF is considered, therefore there is no force or moment in the Y axes. All the differential equations are written in the body coordinate frame. Because aerodynamic and thrust forces and moments can be easily defined in the body coordinate frame. For 3-DOF simulation, the used differential equations are given in Eqs. (4.1), (4.2), (4.3), and (4.4) [38].

$$\dot{u} = \frac{F_x}{m} - w \cdot q \tag{4.1}$$

$$\dot{w} = \frac{F_z}{m} + u \cdot q \tag{4.2}$$

$$\dot{q} = \frac{M_y}{I_{yy}} \tag{4.3}$$

$$\dot{\theta} = q \tag{4.4}$$

## 4.2 Earth Parameters Block

In this block, attitude, direction cosine matrix (inertial reference axis to body axis), and mass values are used in order to calculate the speed of sound, density, and gravitational force values. Simulink Inertial Standard Atmosphere (ISA) Model and WGS84 Gravity Model blocks are used for this aim. Figure 4.4 shows the Earth Parameters Block details.

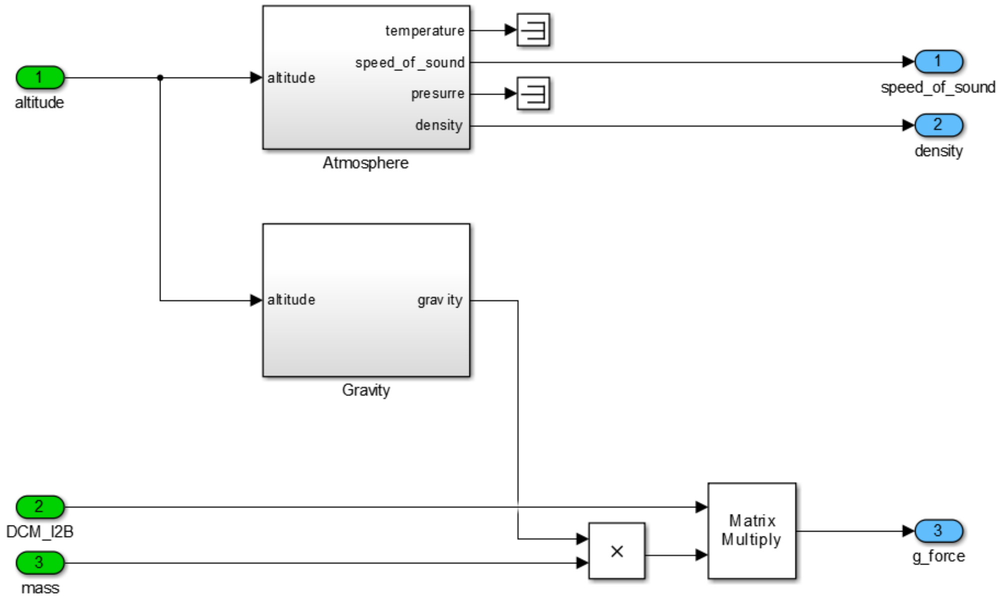



Figure 4.4: Earth Parameters Block

## 4.3 Mass and Inertia Block

In this block, mass, inertia, and center of gravity values change with respect to time are found. To calculate the missile parameters such as weight, propulsion weight, and thrust values size estimation formulas are used. The weight and size estimation equations are given in Eqs. (4.5), (4.6), (4.7) and (4.8) [39]. In Figure 4.5 details of mass and inertia block can be seen.

$$V_{Total} = \frac{(\pi \cdot d^2 \cdot L_{Total})}{4} \tag{4.5}$$

$$W_{Total} = 123.9 \cdot (V_{Total})^{0.985} \tag{4.6}$$

$$\rho_{Total} = \frac{W_{Total}}{V_{Total}} \tag{4.7}$$

$$W_P = 154.3 + 80.6 \cdot V_P \tag{4.8}$$

Inertia values are calculated using estimated equations. For this purpose, missile is assumed as consist of two basic separate parts such as one cone and one cylinder.

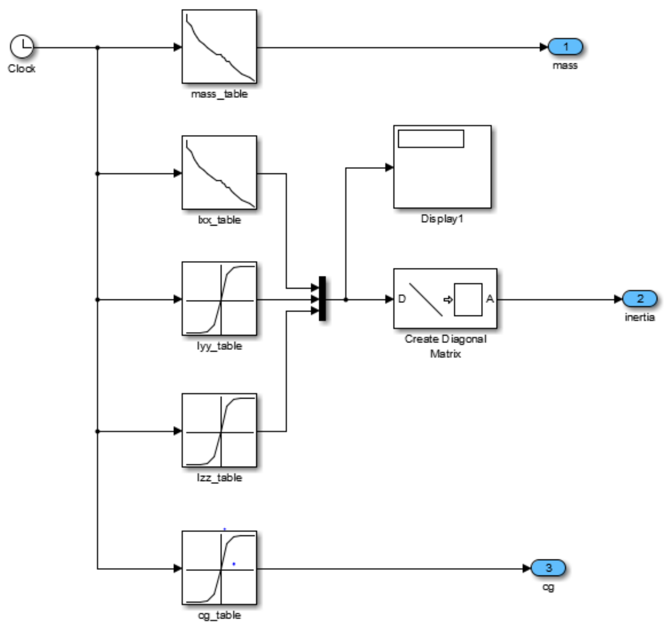



Figure 4.5: Mass and Inertia Block

## 4.4 Aerodynamic Parameters Block

Aerodynamic block is one of the most important blocks for a model. It calculates the aerodynamic forces and moments using the other blocks outputs such as mass, flight conditions, dynamic pressure, center of gravity, etc. To calculate the aerodynamic forces and moments, aerodynamic coefficients should be known. With the help of Missile Datcom, the required aerodynamic coefficients for 3-DOF model are calculated. The required aerodynamic coefficients are $C_x$, $C_z$, $C_{z_q}$, $C_{Z_{\dot{\alpha}}}$, $C_M$, $C_{M_\alpha}$ and $C_{M_{\dot{\alpha}}}$. To calculate aerodynamic forces and moments Eqs. (4.9), (4.10), and (4.11) are used for 6-DOF motion.

$$F_{aero} = Q \cdot S_{REF} \begin{bmatrix} C_X(M,\alpha,\beta,\delta_e) \\ C_Y(M,\beta,\delta_r,\dot{\beta},r) \\ C_Z(M,\alpha,\delta_e,\dot{\alpha},q) \end{bmatrix} \qquad (4.9)$$

$$F_{aero} = Q \cdot S_{REF} \begin{bmatrix} C_X(M,\alpha,\beta,\delta_e) \\ C_Y(M,\beta,\delta_r) + C_{Y_{\dot{\beta}}}(M) \cdot \dot{\beta} \cdot \frac{d}{2 \cdot V_\infty} + C_{Y_q}(M) \cdot q \cdot \frac{d}{2 \cdot V_\infty} \\ C_Z(M,\alpha,\delta_e) + C_{Z_{\dot{\alpha}}}(M) \cdot \dot{\alpha} \cdot \frac{d}{2 \cdot V_\infty} + C_{Z_q}(M) \cdot q \cdot \frac{d}{2 \cdot V_\infty} \end{bmatrix} \qquad (4.10)$$

$$M_{aero} = Q \cdot S_{REF} \cdot L_{REF} \begin{bmatrix} C_L(M,\alpha,\beta,\delta_a) + C_{L_p}(M) \cdot p \cdot \frac{d}{2 \cdot V_\infty} \\ C_M(M,\alpha,\delta_e) + C_{M_{\dot{\alpha}}}(M) \cdot \dot{\alpha} \cdot \frac{d}{2 \cdot V_\infty} + C_{M_q}(M) \cdot q \cdot \frac{d}{2 \cdot V_\infty} \\ C_N(M,\beta,\delta_r) + C_{N_{\dot{\beta}}}(M) \cdot \dot{\beta} \cdot \frac{d}{2 \cdot V_\infty} + C_{N_r}(M) \cdot r \cdot \frac{d}{2 \cdot V_\infty} \end{bmatrix} \qquad (4.11)$$

In order to calculate 3-DOF forces and moment, Eqs. (4.9), (4.10), and (4.11) turns to Eq. (4.12), (4.13), and (4.14).

$$F_{aero} = Q \cdot S_{REF} \begin{bmatrix} C_X(M,\alpha,\delta_e) \\ 0 \\ C_Z(M,\alpha,\delta_e,\dot{\alpha},q) \end{bmatrix} \qquad (4.12)$$

$$F_{aero} = Q \cdot S_{REF} \begin{bmatrix} C_X(M,\alpha,\delta_e) \\ 0 \\ C_Z(M,\alpha,\delta_e) + C_{Z_{\dot{\alpha}}}(M,\alpha) \cdot \dot{\alpha} \cdot \dfrac{d}{2 \cdot V_\infty} + C_{Z_q}(M,\alpha) \cdot q \cdot \dfrac{d}{2 \cdot V_\infty} \end{bmatrix} \tag{4.13}$$

$$M_{aero} = Q \cdot S_{REF} \cdot L_{REF} \begin{bmatrix} 0 \\ C_M(M,\alpha,\delta_e) + C_{M_{\dot{\alpha}}}(M,\alpha) \cdot \dot{\alpha} \cdot \dfrac{d}{2 \cdot V_\infty} + C_{M_q}(M,\alpha) \cdot q \cdot \dfrac{d}{2 \cdot V_\infty} \\ 0 \end{bmatrix} \tag{4.14}$$

## 4.5 Propulsion Block

Thrust can be defined as the reaction force that pushes the missile forward. Thrust can be generated with the help of ejection of combustion gases from the nozzle at a very high velocity. In this study, propulsion block is used to calculate the thrust force. For this aim again some estimation formulas are used. One of the important parameters for thrust calculation is total impulse which can be defined as the time integral of the thrust over the operating time of the rocket engine.

$$I_t = \int_0^{t_b} F \cdot dt \tag{4.15}$$

where;

$F$ is thrust (N) and $t_b$ is burning time (s). Negligible start and stop transients for a constant thrust.

$$I_t = F \cdot t_b \tag{4.16}$$

A time-averaged specific impulse can be written as;

$$I_{sp} = \frac{\int_0^{t_b} F \cdot dt}{g_0 \cdot \int_0^{t_b} \dot{m}_p \cdot dt} \tag{4.17}$$

where;

$\dot{m}_p$ is total mass flow rate of the propellant (fuel and oxidizer) (kg/s) and $g_0$ is standard acceleration of gravity at sea level which is 9.8066 m/s$^2$. For constant thrust and propellant mass flow rate Eq. (4.17) can be written as;

$$I_{sp} = \frac{I_t}{m_p \cdot g_0} = \frac{I_t}{w_p} = \frac{F}{\dot{m}_p \cdot g_0} = \frac{F}{\dot{w}_p} \tag{4.18}$$

where;

$m_p$ is the total effective propellant mass (kg), $w_p$ is the propellant weight (N) and $\dot{w}$ is the propellant weight flow rate (N/s).

Required propellant weight flow rate to produce a unit thrust force, which can be described as specific propellant consumption can be formulated as Eq. (4.19) and also, the mass ratio of a rocket can be written as Eq. (4.20)

$$SPC = \frac{1}{I_{sp}} = \frac{\dot{w}_p}{F} \tag{4.19}$$

$$MR = \frac{m_f}{m_o} \tag{4.20}$$

where;

$m_f$ is the final mass of vehicle after all of the propellant mass was consumed and $m_o$ is the initial mass of the vehicle before rocket was launched.

## 4.6 Flight Conditions

This block is used to calculate required flight condition parameters. It takes as an input, body velocity, speed of sound and density values and gives as an output alpha, airspeed, Mach and dynamic pressure values which are used in the other blocks. Figure 4.6 shows the flight conditions block.

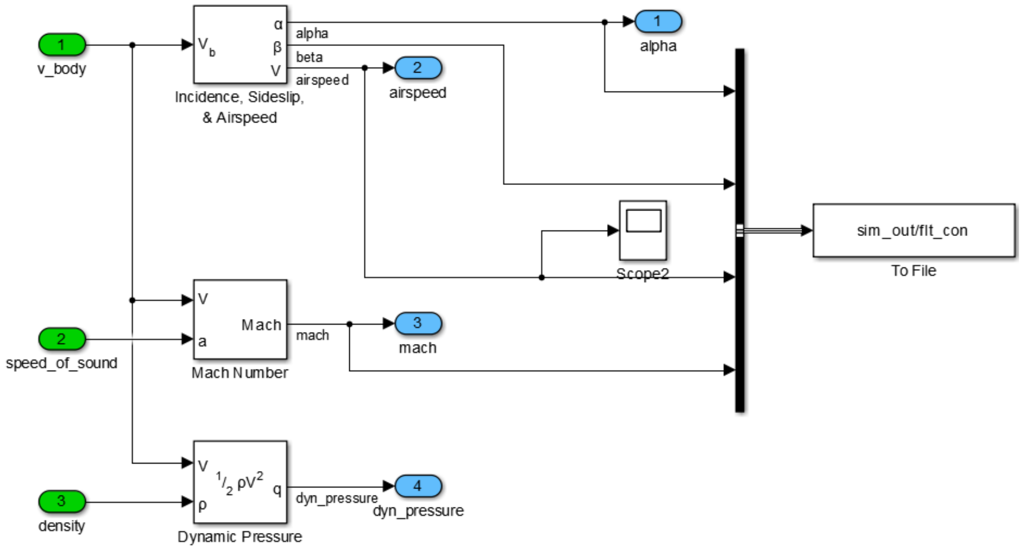



Figure 4.6: Flight Conditions Block

# CHAPTER 5

# CASE STUDIES OF BMOT

In this part, the progress of the BMOT is given and four different case studies are done. At the beginning of the BMOT design process, the aim is having a quick solution during the conceptual design studies.  When it is first created, the main objective is maximizing the ballistic range of the missile, so it only focuses on the range. However, over time, BMOT is developed to optimize both range and maneuverability. While stability and controllability are taken as constraints, range and maneuverability are taken as main object functions. At that point, it should be noted that it can work to optimize only the range or only to optimize maneuverability while it can work to optimize both at the same time.

In addition, since one of the main objectives in the development of this design tool is to achieve a quick solution in the conceptual design studies, an extra effort is made to minimize computational time. Different alternatives are tried. Alternative scenarios are created and tested in order to reach optimum result faster way.

The first case study aimed to compare two different optimization methods. The results of the optimization algorithm based on the commonly used sequential quadratic programming and the created genetic algorithm optimization method based on the evolution theory, which is increasingly popular nowadays, are compared. The same initial values are given as the input to both optimization techniques and results are examined. In addition, in this case study, genetic algorithm tool which is one the embedded tool of Matlab, is used and the performance of this tool and designed optimization algorithm are compared.

The second case study is conducted in order to explain the whole design process in detail. In other words, BMOT design stages from beginning to end are shown.

The third case study shows the ways of achieving the optimum result as soon as possible, and the alternative scenario results are given. On the other hand, the fourth case study aims to show how the design changes when the object function focus point changes.

In all case studies, a surface to surface tail controlled ballistic missile is used. Its external geometry properties are taken as reference missile parameters. Using the reference missile parameters maximum and minimum values are determined.

## 5.1 Case Study I

The purpose of this study is to compare sequential quadratic programming and genetic algorithm and to see which method is more suitable for BMOT. As sequential quadratic programming, fmincon, one of Matlab embedded function is used, while for genetic algorithm, both of the created genetic algorithm code and embedded Matlab tool, which is GAtool are used.

To make a valid comparison, same objective function and constraints are given all optimization tools with same inputs and boundary conditions. Objective function is aimed to maximize the range, so the drag force which is considered in the fitness function should be minimized. In other words, the design with minimum fitness value has best range capabilities.

Genetic algorithm optimization tool starts with the creating an initial population around given initial value and try to find the optimum result with combining these population individuals, so it reaches most probably, the global optimum result. On the other hand, fmincon is focused to find the next optimum result. Initial value should be chosen around global optimum, to find the best possible solution. Therefore, it is very dependent on the initial value given. In Table 5.1 comparison of optimization methods with respect to fitness, values are given.

Table 5.1: Comparison of optimization methods

| **Optimization Technique** | **Fitness Value** |
|---|---|
| Created GA tool | 2,6326 |
| fmincon | 3,0227 |
| Matlab GAtool | 2,8628 |

It is seen that created genetic algorithm tool has the best fitness value. When this situation is examined, it is thought that fmincon should be in a local minimum, because of fact that, if there is a local minimum around the given initial value, the probability of finding it increases. In order to compare performance between created GA tool and Matlab GAtool, the population used in created GA is taken and a function is created with Matlab embedded regress function. It is believed, improving this function should be improved the result of the Matlab GAtool.

In order to test if fmincon is found a local minimum, the initial point is replaced with another point known to have a better fitness value and the analysis is repeated. Results are given in Table 5.2.

Table 5.2: Comparison of fmincon with different initial point

| **Optimization Technique** | **Fitness Value** |
|---|---|
| Created GA | 2,6326 |
| fmincon | 3,0227 |
| fmincon (new initial guess) | 2,8108 |

With changing initial point, fmincon fitness value approaches created GA fitness value, which is closer to the global optimum result. In Figure 5.1 comparison of fitness values with respect to different optimization techniques are given.

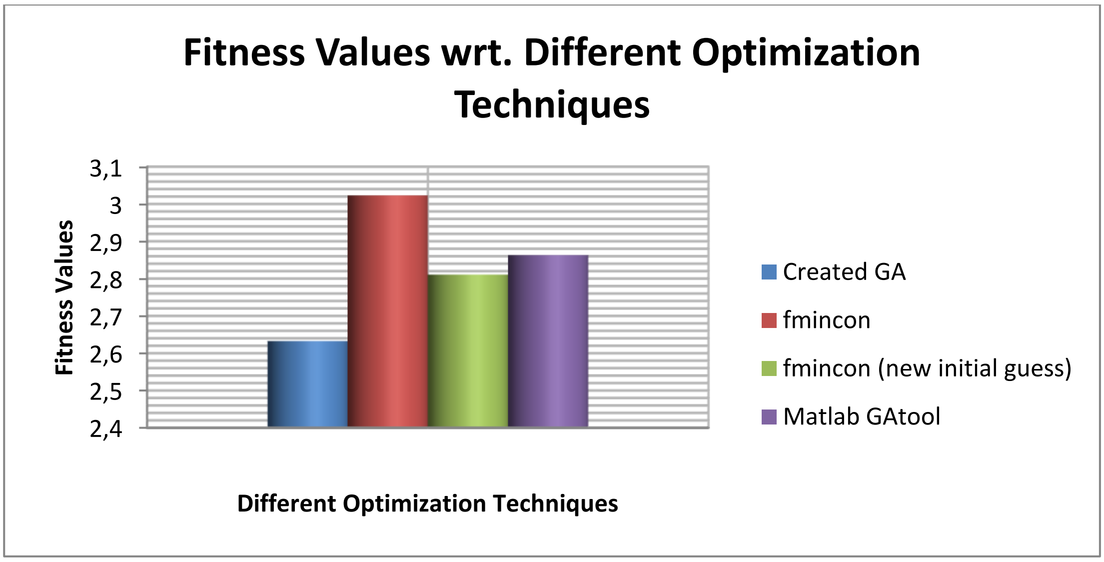



Figure 5.1: Fitness Value Changes for Different Optimization Techniques

## 5.2 Case Study II

In the second case study, the whole design process is tried to give in detail. For this aim, a surface to surface tail controlled ballistic missile is used. Its external geometry properties are taken as a reference. Since the reference missile's aerodynamic information is not known, the aerodynamic database is produced by Missile Datcom with using BMOT aerodynamic design part.

To start new external geometry design, the maximum and minimum values are defined for all 11 parameters which are called as genes. In this study, chromosome number, which represents the solution itself, is selected as 50 and the generation number which represents iteration number is selected as 5 for optimization loop of genetic algorithm. A *[50 x 11]* dataset is created as a first population. Population can be defined as designed space which includes all possible solution or in other words, chromosomes.

As a first step, the constraints should be checked. While designing new external geometries, there exist some constraints that restrict the scope of the problem and determine the boundaries of design parameters. Some constraints can be due to launch platform limitations, and they can be taken into account in the determination of the maximum/minimum values. However, some constraints are directly related to performance such as stability and control effectiveness. It should be noted that all the chromosomes in this dataset satisfy the constraints which means all the genes provide the requirements of the constraint. Thus, all of them are statically stable and controllable.

As a next step, the genetic algorithm started. Created population's fitness values are calculated and normalized. According to fitness values, all the chromosomes have a probability of selection. In this study, the aim is to find the minimum fitness value and so, the chromosome that has a minimum fitness value, selection probability is higher than the others according to the "roulette-wheel" selection. When the parents are selected, the crossover starts. Randomly, crossover point is decided, and children are generated with respect to this point. In Figure 5.2 single point crossover in BMOT is illustrated.

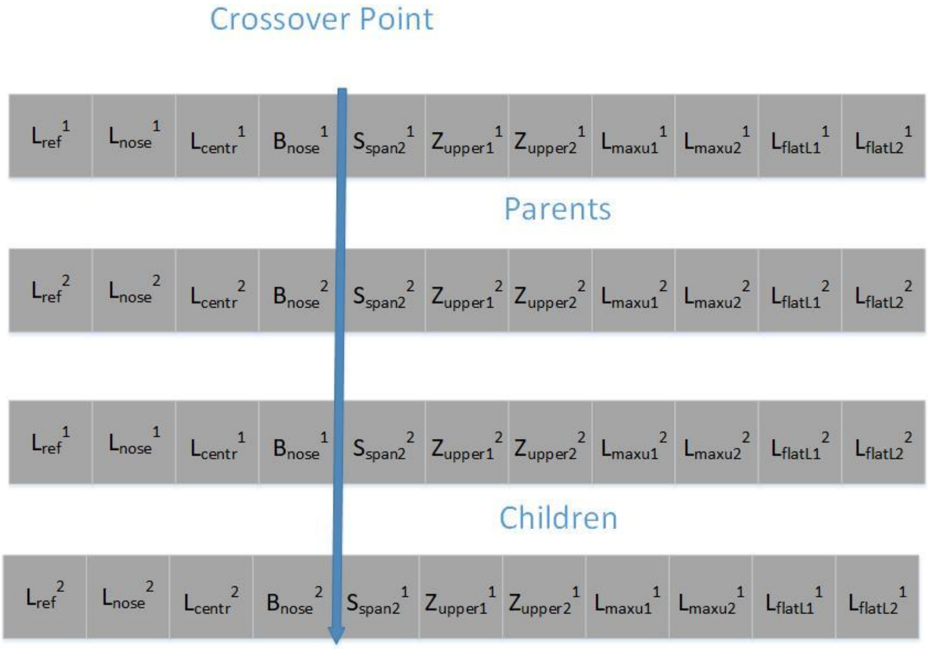



Figure 5.2: Single Point Crossover of BMOT Parameters

When the crossover part is finished, 4 different alternatives are generated which can be seen in Figure 5.3.

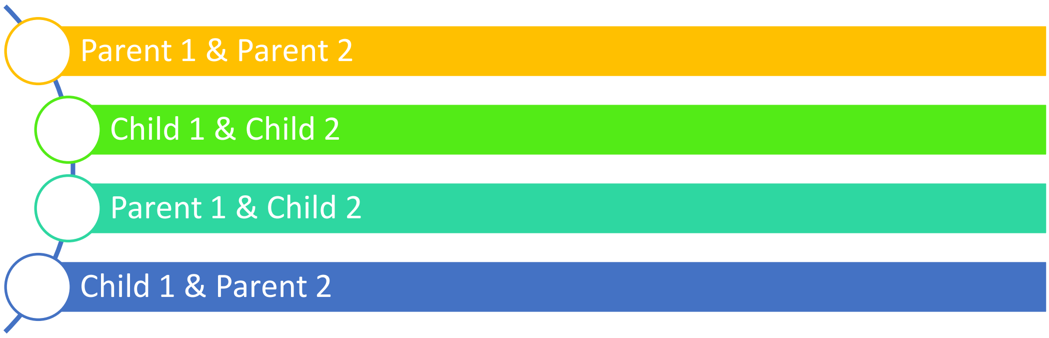



Figure 5.3: Alternative Crossover Results

The new generation of individuals is decided randomly according to the probability of crossover. After that, mutation is done with respect to, the probability of mutation. The last but not least step is elitism. The chromosome which has the best fitness values is directly carried to the next population.

This loop is repeated until the generation number or iteration number is reached the desired maximum generation. As a result, the optimum geometry and its fitness value are given by the genetic algorithm part. The best chromosome is taken to the Datcom in order to create the aerodynamic database. After that, this database is used in performance analysis in 3-DOF model. In Table 5.3 fitness values of missiles are given. And also, in Figure 5.4 normalized trajectories are given.

Table 5.3: Fitness Values of Missiles

| | **Fitness Value** |
|---|---|
| **Reference Missile** | 3,1184 |
| **Optimized Missile with BMOT** | 2,6549 |

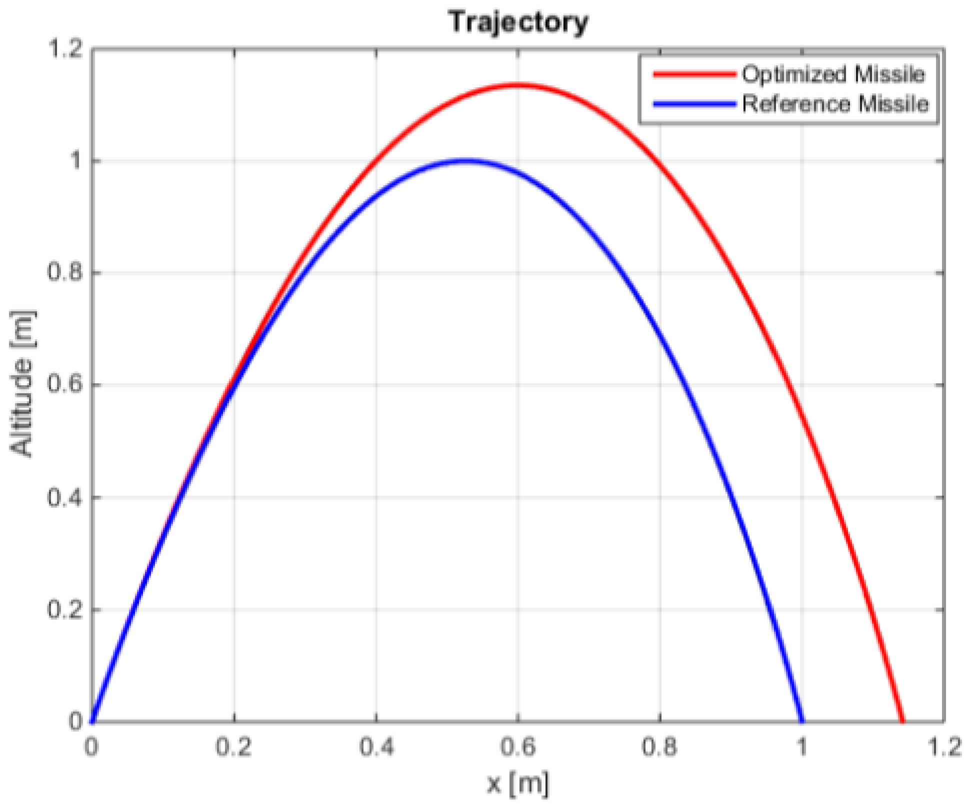



Figure 5.4: Normalized Trajectory of Missiles

## 5.3 Case Study III

The aim of this study is to get the optimum missile design, which has the best maneuverability and ballistic range values, in the shortest time. Before starting the design, different chromosome numbers and generation numbers are selected. In order to see the effect of these numbers, all of them tried one by one.

As expected, increase of the chromosome number and generation number has a positive effect on the fitness value. On the other hand, while the fitness increases linearly, time spent during the design increase exponentially. To choose optimum chromosome and generation number some analysis is done.

In Figure 5.5, Figure 5.6, Figure 5.7, and Figure 5.8 change of the fitness values and time for different chromosome numbers are given. To test the effect of the chromosome number four different chromosome numbers are selected. These are 20, 100, 500, and 1000. As mentioned before, the increase in fitness values and time are compared. It is clearly seen that increment of the chromosome number causes too long computational time. Such that while 20 chromosomes and 10 generation number run take 11 minutes, 1000 chromosome numbers and again 10 generation number run takes 624 minutes.  At that point, it should be stated that; fitness value change is approximately %25 while computational time 56 times increases.

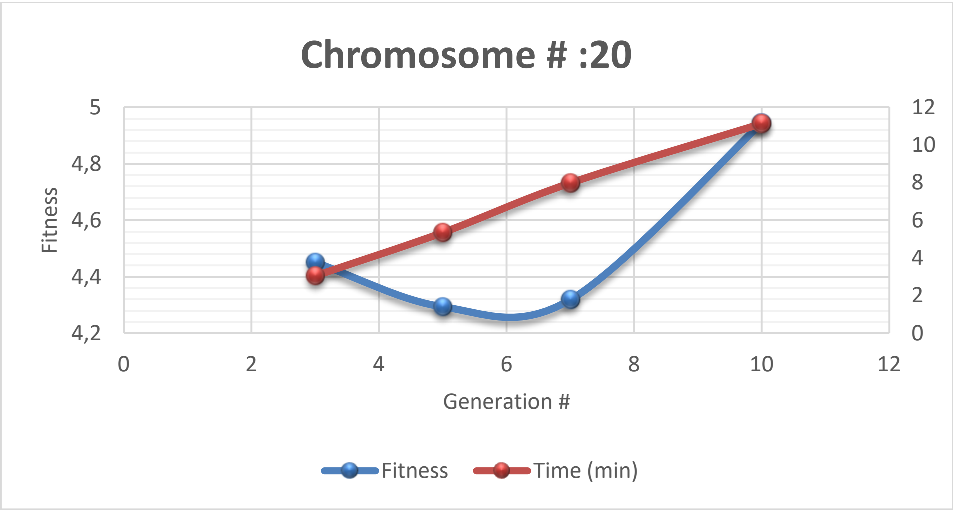



Figure 5.5: Fitness and Time vs. Generation Number for Chromosome # : 20

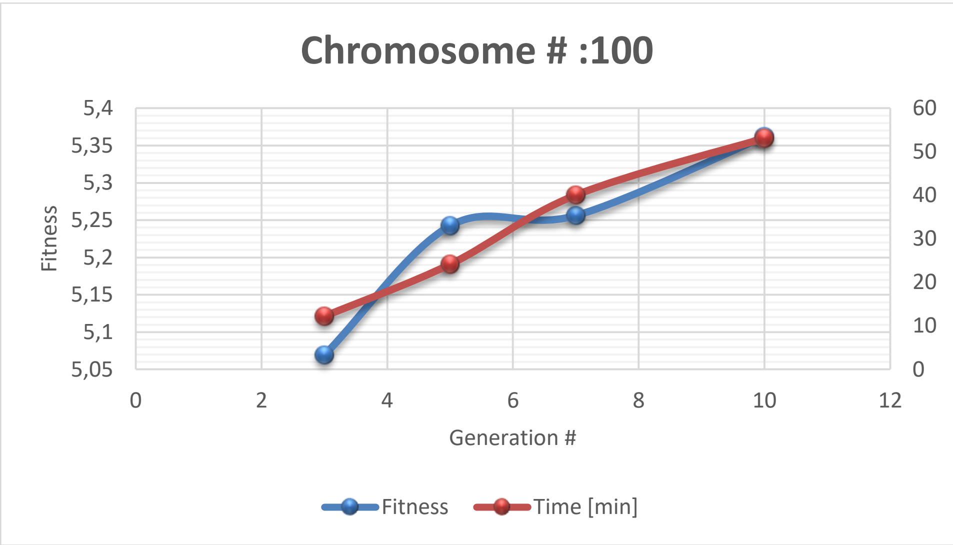



Figure 5.6: Fitness and Time vs. Generation Number for Chromosome # : 100

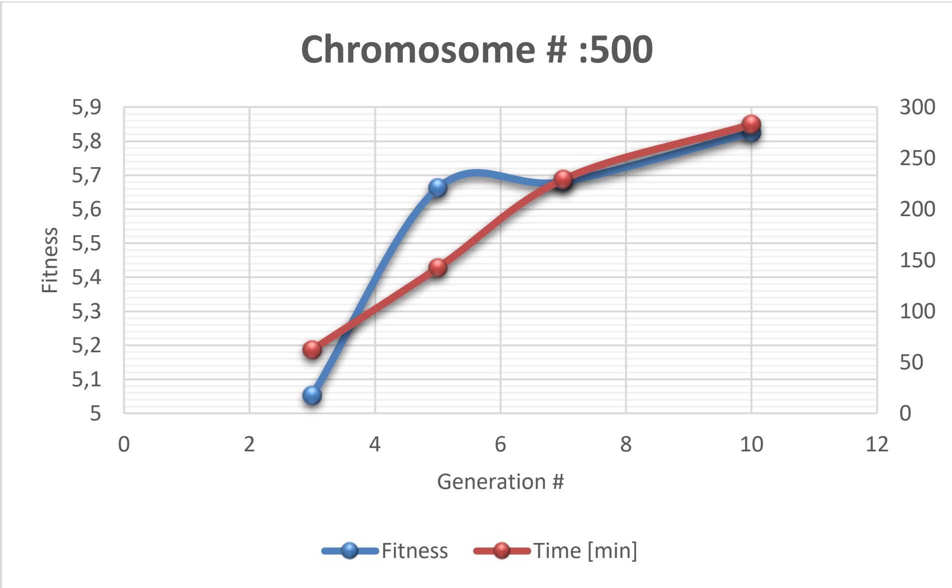



Figure 5.7: Fitness and Time vs. Generation Number for Chromosome # : 500

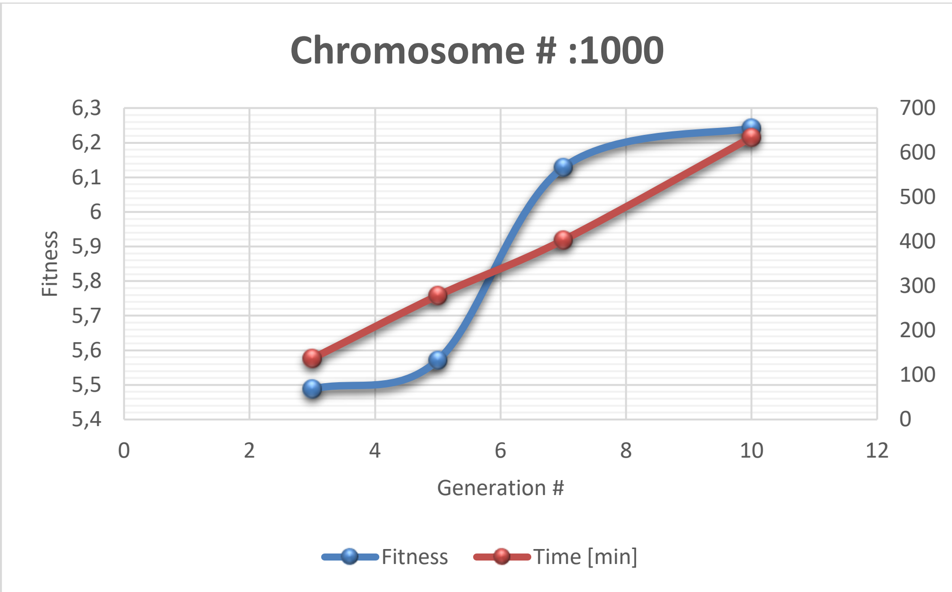



Figure 5.8: Fitness and Time vs. Generation Number for Chromosome # : 1000

Figure 5.9, Figure 5.10, Figure 5.11, and Figure 5.12 shows the change of the fitness and time values with respect to chromosome numbers for constant generation number. For this aim generation numbers are selected as 3, 5, 7, and 10. Like above figures, when the generation number increases computational time increases but not like chromosome number changes. For example, 500 chromosome number and 3 generation number optimization case take 62 minutes while 500 chromosome number and 10 generation number case 634 minutes. The fitness values of these run change 15% while time increases 4.5 times.

In later steps, when deciding chromosome and generation number values these fitness value changes, and time increments are taken into account. It is decided to work on a scenario that found a faster and better solution.

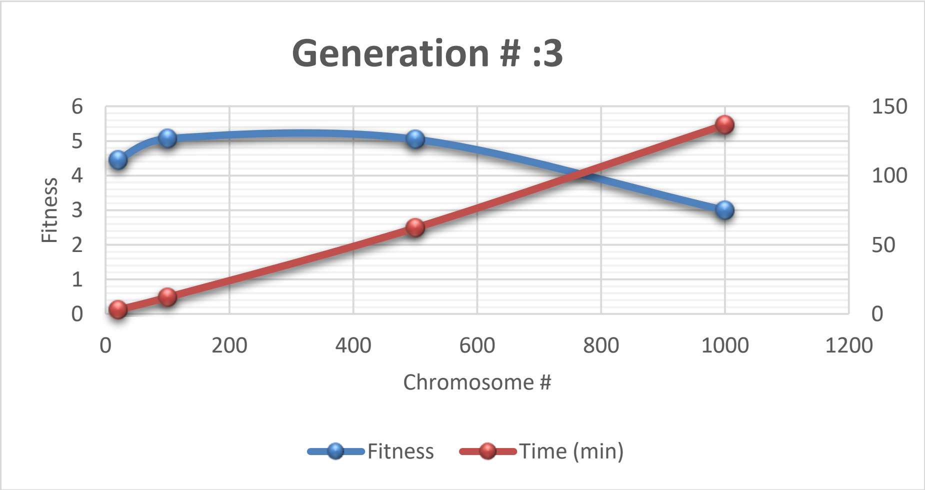



Figure 5.9: Fitness and Time vs Chromosome Number for Generation #: 3

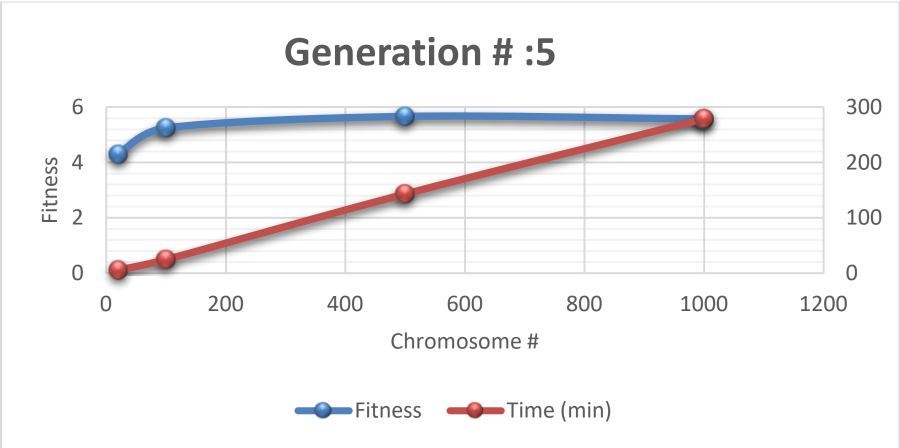



Figure 5.10: Fitness and Time vs Chromosome Number for Generation #: 5

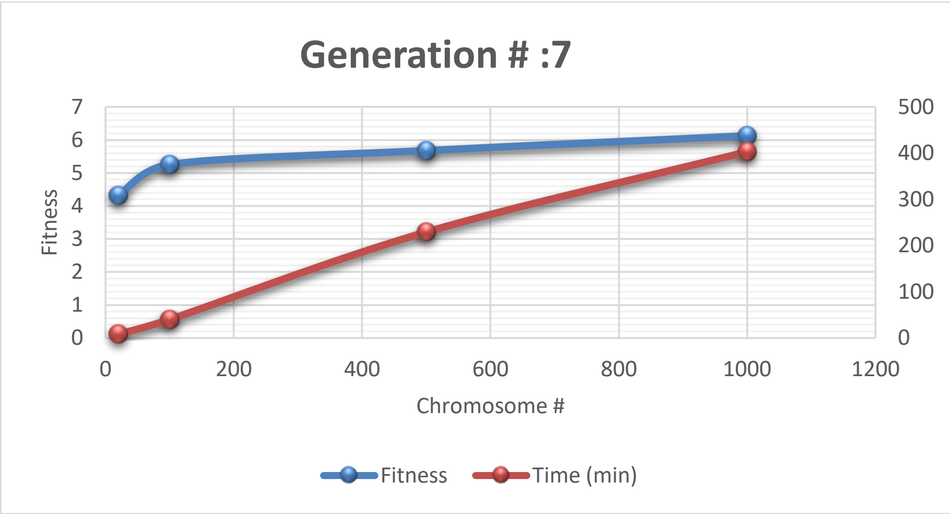



Figure 5.11: Fitness and Time vs Chromosome Number for Generation #: 7

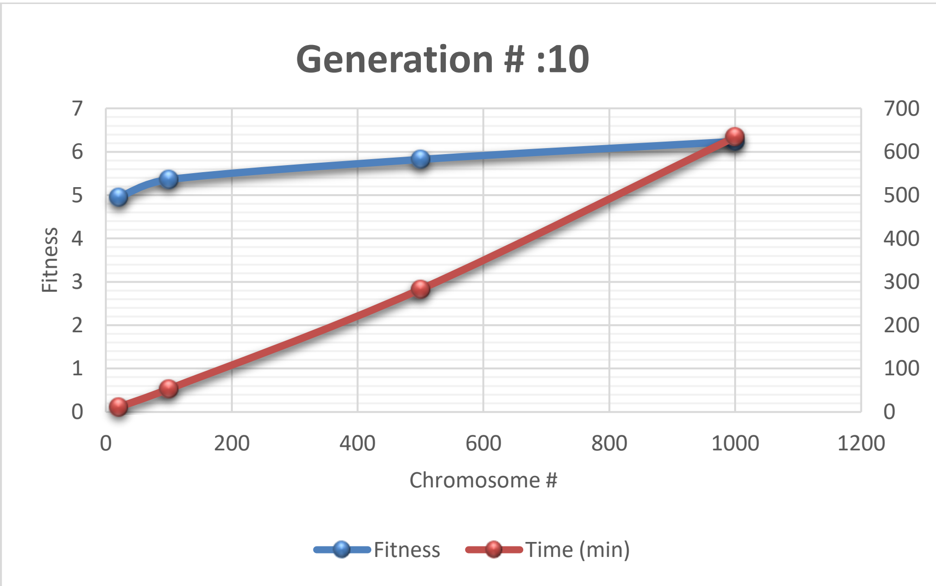



Figure 5.12: Fitness and Time vs Chromosome Number for Generation #: 10

As a next step, different alternatives optimization loops are tried with different chromosome numbers. It is aimed to test whether the BMOT result is optimum or not. When the optimization is finished, its best result is taken, and each parameter is changed ±1 % one by one. Twenty-two separate run is done, it is seen that both worse results and better results are possible. When this situation is examined, if the chromosome number is higher, the less likely the better results encountered. In other words, while the optimization loop is conducted, if the chromosome number is not large enough, the required genetic diversity is not satisfied. So, it is discovered that larger chromosome numbers in the optimization cycle improve the results. On the other hand, when the chromosome number is increased, the solution time increased exponentially. Therefore, it is decided to start looking to answer whether it is possible to find alternative solutions.

After this step, chromosome number is selected as 300 and generation number is selected as 6. It is seen that this run is also taken longer than expected. The results are given below Table 5.4.

Table 5.4: BMOT Results (Chromosome # 300 and Generation # 6)

| **Chromosome#: 300 Generation # : 6** | **Fitness** | **Time [min]** |
|---|---|---|
| | 5,7395 | 130 |

As a next step, another alternative process is tried. It is aimed to test whether the same result can be obtained by trying more than one run with a smaller number of chromosome number instead of one run with larger chromosome number. For this purpose, different chromosome numbers are selected and tried. In multiple run conditions, the output of the previous optimization is given as input to the next. In every iteration, all the constraints and mechanical limits are checked. If the design does not provide requirements, it is directly eliminated. Results are given in Table 5.5. The fitness values are normalized to compare easily. It is seen that this is a very efficient method. The run, which has 300 chromosome numbers, has the best fitness value. So, when normalizing the fitness values, it is assumed that maximum fitness value can be called as 1. The second alternative run which chromosome number is 30, can reach 0.9811 normalized fitness value after 4 runs and in 47.48 minutes while the third run which chromosome number is selected as 20, can reach 0.9598 normalized fitness value as 49.76 minutes.

Table 5.5: Alternative Optimization Loop Results – I

| | **Fitness** | **Norm. Fitness** | **Time [min]** |
|---|---|---|---|
| **Chromosome# : 300**<br>**Generation # : 6** | 5,7395 | 1 | 130 |

| | **Run #** | **Fitness** | **Norm. Fitness** | **Time [min]** |
|---|---|---|---|---|
| **Chromosome#: 30**<br>**Generation # : 6** | **Run 1** | 4,7035 | 0,8194 | |
| | **Run 2** | 5,4442 | 0,9485 | |
| | **Run 3** | 5,2194 | 0,9093 | |
| | **Run 4** | 5,6313 | 0,9811 | 47,48 |

| | **Run #** | **Fitness** | **Norm. Fitness** | **Time [min]** |
|---|---|---|---|---|
| **Chromosome#: 20**<br>**Generation # : 6** | **Run 1** | 4,3111 | 0,7511 | |
| | **Run 2** | 4,6113 | 0,8034 | |
| | **Run 3** | 4,859 | 0,8465 | |
| | **Run 4** | 5,0615 | 0,8818 | |
| | **Run 5** | 5,1673 | 0,9003 | |
| | **Run 6** | 5,4279 | 0,9457 | |
| | **Run 7** | 5,5093 | 0,9598 | 49,76 |

To check the validity of this method another study is done. This time generation number is selected as 10 and different chromosome numbers are tried to compare their results with respect to time.

As a first step, very high chromosome number such as 500 is chosen. Its results are given in Table 5.6.

Table 5.6: BMOT Results (Chromosome # 500 and Generation # 10)

| **Chromosome#: 500 Generation # : 10** | **Fitness** | **Time [min]** |
|---|---|---|
| | 6,1066 | 352 |

It took too long to reach the conclusion as expected. The above procedure is repeated to see the alternative design solution. Results are given in Table 5.7.

Table 5.7: Alternative Optimization Loop Results – II

| **Chromosome# : 500 Generation # : 10** | **Fitness** | **Norm. Fitness** | **Time [min]** |
|---|---|---|---|
| | 6,1066 | 1 | 352 |

| | **Run #** | **Fitness** | **Norm. Fitness** | **Time [min]** |
|---|---|---|---|---|
| **Chromosome# : 50 Generation # : 10** | **Run 1** | 5,5689 | 0,9119 | |
| | **Run 2** | 5,8548 | 0,9587 | |
| | **Run 3** | 6,0874 | 0,9968 | 135 |

When above two studies are examined, it is seen that giving the best previous result to the next case is a good way for this optimization problem.

The calculations are done on a computer having a processor Intel Core i7-4790K CPU @ 4.00 GHz with 16,00 GB of RAM.

## 5.4 Case Study IV

As mentioned in previous section BMOT can be used for two aims. The first one is maximizing range and the second one is maximizing maneuverability. These objectives can be considered together or one by one. In this study, it is aimed to show the geometry change in case of different objective. The fitness function is defined as Eq. (5.1).

$$F(x) = A \cdot f(x) - B \cdot g(x) \tag{5.1}$$

where;

A: Weight of the Maneuverability Function

B: Weight of the Range Function

To increase or decrease these $f(x)$ $g(x)$ and functions weight A and B values can be changed. In addition, to eliminate the effect of $f(x)$ or $g(x)$, A and B can be chosen as zero. The first part of this study A is chosen as 0, so the BMOT try to find the design which has the maximum range. The second part of this study B is chosen as 0, so BMOT tries to optimize maneuverability, and as a last step, A and B values are chosen equally to find the design which has maximum range and maneuverability together. In the end, the geometries are compared.

Configuration I → BMOT optimizes missile ballistic range.

Configuration II→ BMOT optimizes maneuverability of the missile.

Configuration III→BMOT optimizes both range and maneuverability at the same time.

Table 5.8: BMOT Results

| Parameters | Conf-1 | Conf-2 | Conf-3 |
|---|---|---|---|
| LREF | 11,75 | -4,68 | 2,05 |
| LNOSE | 19,15 | -7,62 | 15,58 |
| LCENTR | 7,55 | 1,82 | 1,67 |
| BNOSE | -9,18 | 7,06 | -14,20 |
| SSPAN2 | -18,96 | 6,25 | 7,99 |
| ZUPPER1 | 14,43 | 7,59 | -14,50 |
| ZUPPER2 | -8,49 | 15,70 | -11,48 |
| LMAXU1 | 11,66 | -18,46 | 6,92 |
| LMAXU2 | -10,78 | 18,40 | -12,29 |
| LFLATL1 | -16,59 | 8,00 | -17,57 |
| LFLATL2 | -7,58 | 19,14 | 19,04 |

Table 5.8 represents the change percentage of the optimization parameters. Reference missile is taken as baseline.

In Figure 5.13 change percent with respect to different configurations are given. It is seen that for different cases different optimization results are created. Because of maneuverability is related to the normal force and normal force is related to the fin configuration, in configuration 2, BMOT increases control surface area. For this aim, fin configuration parameters such as; sspan2, zupper, lmaxu, lflatu, etc. values are increased. On the other hand, for configuration 1, its aim is to increase the range of the missile. So, the drag coefficient should be decreased. For this purpose, the control surface lengths are reduced. However, due to the controllability constraint, there exists a limit. This prevents nonsensical designs occurs.

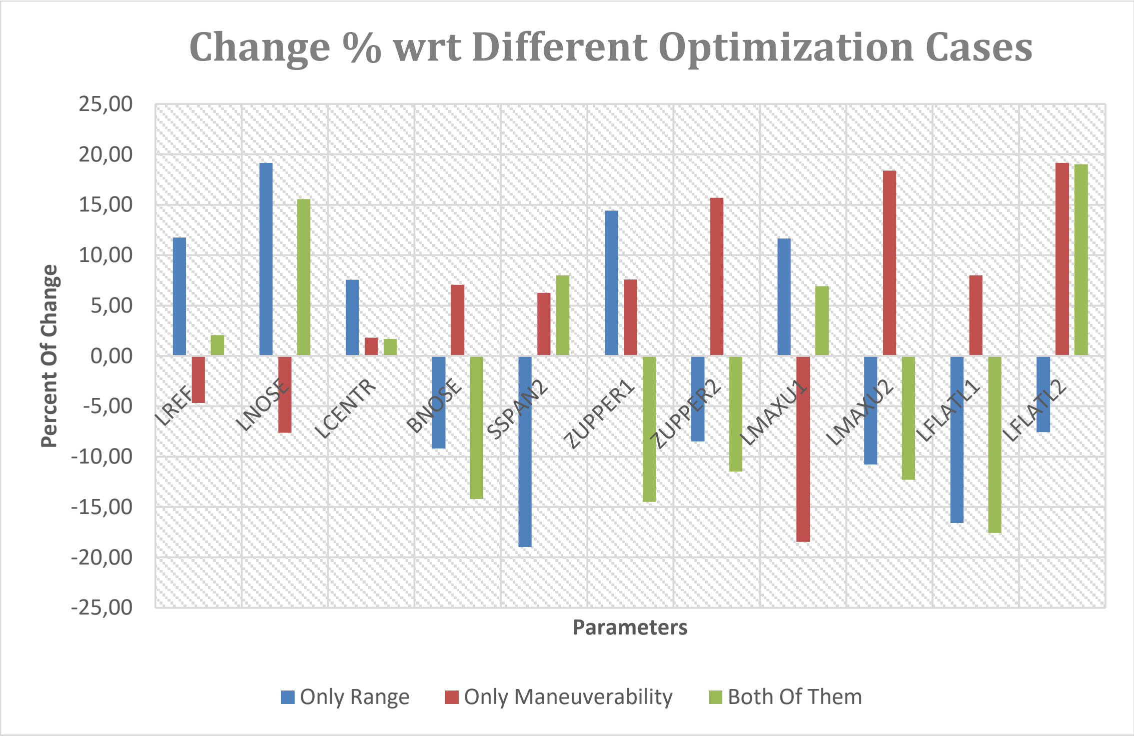



Figure 5.13: Change % wrt Different Optimization Cases

The sketch representation of the designed three configurations is given in Figure 5.14.

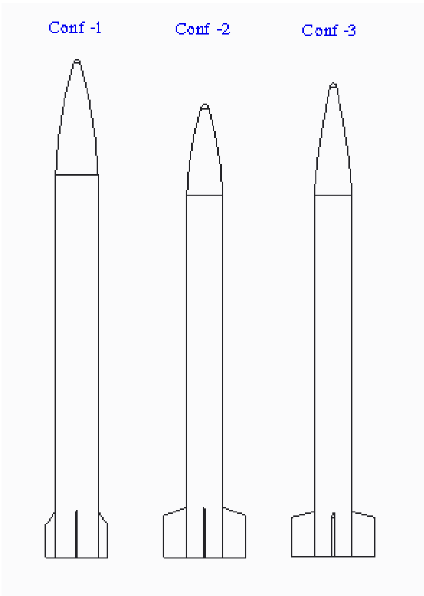



Figure 5.14: Sketches of Alternative Designs

In Figure 5.15, comparison of ballistic missile normalized ranges is given. The three configurations and their reference missile ballistic ranges are given. It is seen that BMOT can optimize the ranges if the objective is given as a range.

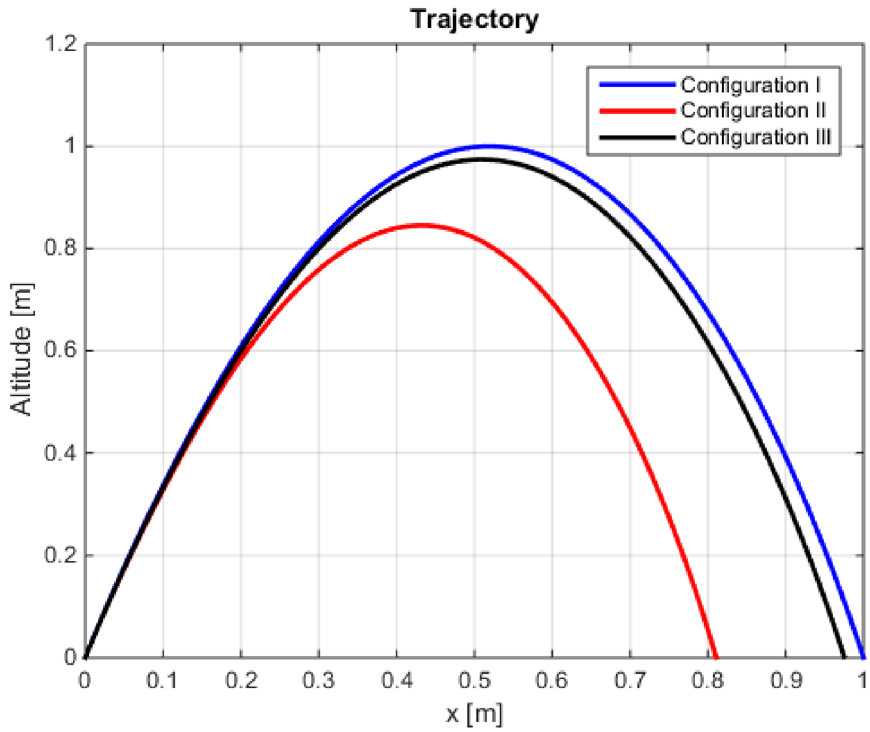



Figure 5.15: Normalized Trajectories of Alternative Designs

# CHAPTER 6

# DISCUSSION AND CONCLUSION

In this study, an optimization tool is created for surface to surface ballistic missile systems. It presents the methodology to design and optimize external geometry of subsonic or supersonic ballistic missiles.

This optimization tool (BMOT), includes three main sections. These are aerodynamic design, optimization and simulation parts. Aerodynamic design part creates alternatives with respect to constraints by using Missile Datcom, optimization part tries to optimize the alternatives, which are come from the aerodynamic part, using Genetic Algorithm, and lastly, simulation part is used to perform analysis with the help of 3-DOF simulation which is created in MATLAB Simulink. By using this tool, configurations are created, analyzed, optimized and tested. As a last step, the best alternative selected.

It should be noted that Ballistic Missile Optimization Tool (BMOT) can be used for conceptual design studies. Its aim is giving the required information for preliminary design as quickly and efficiently.

For Ballistic Missile systems the most important parameters are range and maneuverability. That's why BMOT focuses on them.

Two different case studies are done in order to show the BMOT design capacity. The first case study is aimed to get the optimum missile configuration in the shortest time. For this purpose, different chromosome numbers and generation numbers are selected and tried with BMOT one by one.  To choose the optimum input values analysis are done. It is examined whether the optimization result is the best or not. Alternative scenarios are created to find better results in limited time constraints.

The second case study shows the results of the BMOT for different objective function. In the optimization process, it is possible to focus these parameters one by one or at the same time. Therefore, in this study, all the alternative objectives are tried, and their results are compared. As expected, to maximize maneuverability BMOT focus on the fin configuration design and increase the control surface areas. On the other hand, to maximize range, BMOT tries to change geometry to decrease the drag coefficient. The designed geometries and their trajectories are given and compared.

To sum up, an optimization design tool for the ballistic missile is created and tested in this thesis for conceptual design studies. With the help of this tool, the conceptual design process can be accelerated and the required information for the preliminary design studies can be found.

## 6.1 Future Works

As future work,

- Aerodynamic prediction capabilities can be increased. Instead of Missile Datcom, more accurate methods such as CFD can be used.
- In addition to the surface to surface ballistic missiles, another mission types like surface to air, air to air, etc. can be added.
- In a model control capability can be added. The guided missile and unguided one performance parameters can be compared.
- Trajectory optimization can be done after adding the control sections.
- More objectives like maximization of velocity or minimization of weight can be added.

- Weight and thrust estimations parts can be detailed. More accurate methods like 3D modeling can be done.
- Instead of 3-DOF model 6-DOF model can be created for detailed analysis.
- Other evolutionary algorithms can be used for the optimization section. After that, their results can be compared.

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## APPENDIX A

## EARTH PARAMETERS

In 3-DOF model there exists Earth parameters block. In this block, Simulink Inertial Standard Atmosphere (ISA) Model and WGS84 Gravity Model blocks are used. Details are given below.

### WGS4 Model

To calculate the gravity change with respect to position change Simulink WGS-84 Gravity Model is used. As an input latitude ($^o$), longitude ($^o$) and height (m) are given. An illustration of The World Geodetic System 1984 (WGS84), origin and axes are given Figure A. 1.

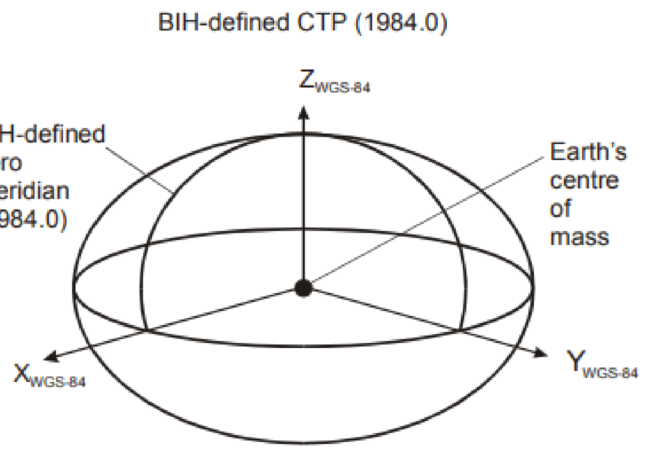



Figure A. 1: WGS84 Coordinate System Definition [40]

Parameters of WGS-84 is given Table A.1.

Table A. 1: Parameters of WGS-84 [40]

| Parameter | Abbreviation | WGS-84 |
|---|---|---|
| Semi-major axis | a | 6378137 m |
| Angular velocity | ω | $7.292115 \times 10^{-5}$ rad $s^{-1}$ |
| Geocentric gravitational constant | GM | 398600.5 $km^3 s^{-2}$ |
| Normalized second degree zonal harmonic coefficient of the gravitational potential | $C_{2,0}$ | $-484.16685 \times 10^{-6}$ |
| Flattening | f | 1/298.257223563 |

**ISA**

To calculate the required atmosphere information such as temperature, pressure, density, and speed of sound international standard atmosphere block (ISA) is used. The only input of the model is altitude (m). The altitude range is -5 to 1000 km. ISA parameters are given in Table A. 2

Table A. 2: Parameters of ISA [41]

| Parameter | Abbreviation | WGS-84 |
|---|---|---|
| Specific heat ratio | γ | 1.4 |
| Absolute temperature @ mean sea level | $T_0$ | 288.15° K |
| Air density @ mean sea level | $\rho_0$ | 1.225 $kg/m^3$ |
| Gravitational acceleration | g | 9.80665 $m/s^2$ |
| Characteristic gas constant | R | 287.05 j /(kg °K) |
| Lapse rate | L | 0.0065° K/m |

# APPENDIX B

## AERODYNAMIC CALCULATIONS WITH MISSILE DATCOM

In rocket/missile conceptual and preliminary design, it is necessary to quickly estimate the aerodynamics of a wide variety of configurations. The geometry of the missile and performance is dependent on the subsystem properties, such as payload weight, propulsion system, launch platform, etc. Therefore, the designer should be capable of predicting a wide variety of configuration accurately. The main purpose of Missile Datcom is to provide an aerodynamic design tool that has the predictive accuracy suitable for conceptual and preliminary design studies.

Table B. 1: Missile Datcom Parameter Definitions

| **Parameter** | **Definition** |
|---|---|
| CN | Normal force coefficient |
| CL | Lift coefficient |
| Cm | Pitching moment coefficient |
| Xcp | Center of pressure in calibers from the moment reference center |
| CA | Axial force coefficient |
| CD | Drag coefficient |
| CY | Side force coefficient |
| Cn | Yawing moment coefficient (body axis) |
| Cl | Rolling moment coefficient (body axis) |
| CNa | Normal force coefficient derivative with angle of attack |
| Cma | Pitching moment coefficient derivative with angle of attack |
| Cmq | Pitching moment coefficient derivative with pitch rate |
| CNq | Normal force coefficient derivative with pitch rate |
| CAq | Axial force coefficient derivative with pitch rate |
| Cmαd | Pitching moment derivative with rate of change of angle of attack |

| 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. |

Figure B. 1: Inputs and Outputs of Missile Datcom

The namelist names for input file are selected as related to their physical meaning. The namelists are given in Table B. 2.

Table B. 2: Input Namelist of Missile Datcom

| **Namelist** | **Inputs** |
|---|---|
| $FLTCON | Flight conditions (angles of attack, altitudes, etc.) |
| $REFQ | Reference quantities (reference area, length, etc.) |
| $AXIBOD | Axisymmetric body definition |
| $ELLBOD | Elliptical body definition |
| $PROTUB | Protuberance information and geometry |
| $FINSETn | Fin descriptions by fin set (n is the fin set number: 1, 2, 3 or 4) |
| $DEFLCT | Panel incidence (deflection) values |
| $TRIM | Trimming information |
| $INLET | Inlet geometry |
| $EXPR | Experimental data |

Each component of the configuration of the missile needs a separate namelist input. For example, an input case of a body, wing and tail configuration requires definition of flight conditions, body definition and fin set details such as locations and dimensions (Table B.3)

Table B. 3: Namelist Inputs (Required)

| **Namelist** | **Definition** |
|---|---|
| $FLTCON | to define the flight conditions |
| $AXIBOD or $ELLBOD | to define the body |
| $FINSET1 | to define the most forward fin set |
| $FINSET2 | to define the first following fin set |

Moreover, there also exist some optional inputs. These values are not required because they have defaults (Table B. 4).

Table B. 4: Namelist Inputs (Optional)

| **Namelist** | **Definition** |
|---|---|
| $REFQ | to define the reference quantities |
| $PROTUB | to define protuberance option inputs |
| $DEFLCT | to define the panel incidence (deflection angles) |
| $TRIM | to define a trim case |
| $INLET | to define inlet geometry |

To define the fin set of a missile, missile's airfoil section, span locations, chord location, chord length, number of fin sets, fin sets locations, thickness to chord ratio, etc. values should be defined. In Table B. finset namelist variable definitions are given Table B.5.

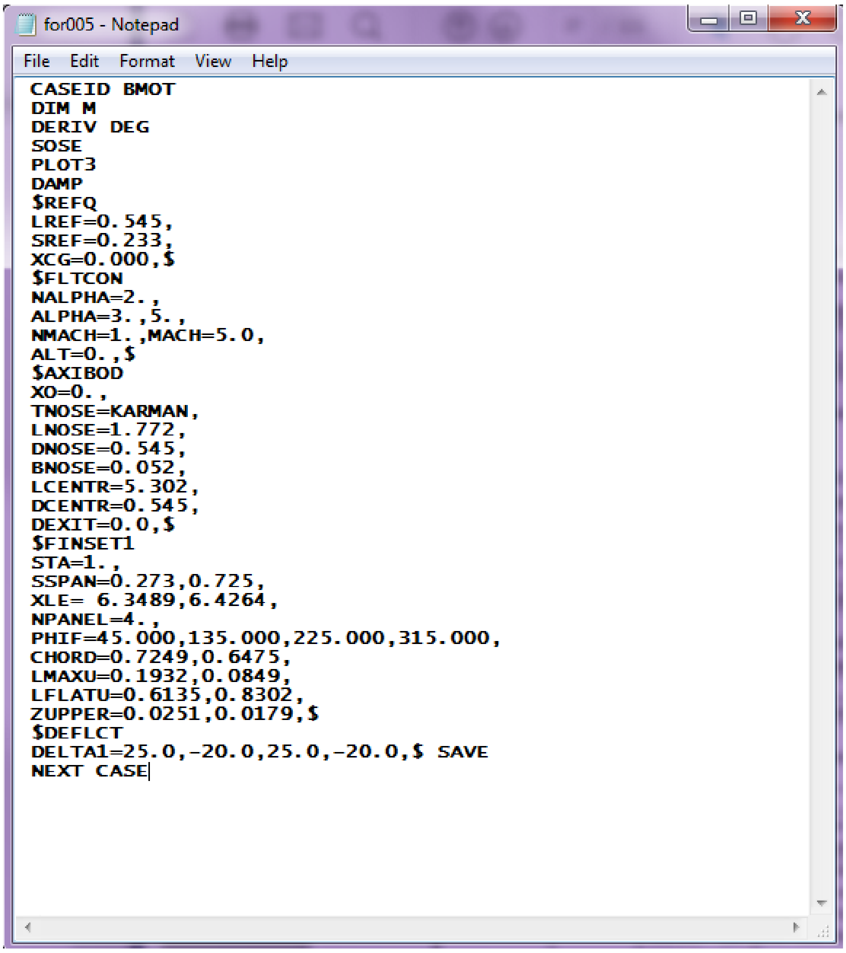
Table B. 5: Missile Datcom FINSET Namelist Variable Definitions

| **Parameter Name** | **Definition** |
|---|---|
| SECTYP | Type of airfoil section |
| SSPAN | Semi-span locations |
| CHORD | Panel chord at each semi-span location |
| XLE | Distance from missile nose to chord leading edge |
| NPANEL | Number of panels in fin set |
| PHIF | Roll angle of each fin measured clockwise top vertical center looking forward |
| ZUPPER | Thickness to chord ratio of upper surface. |
| ZLOWER | Thickness to chord ratio of lower surface. |
| LMAXU | Fraction of chord from section leading edge to maximum thickness of upper surface. |
| LMAXL | Fraction of chord from section leading edge to maximum thickness of lower surface. |
| LFLATU | Fraction of chord of constant thickness section of upper surface. |
| LFLATL | Fraction of chord of constant thickness section of lower surface. |

To define the body of the missile some parameters required to be defined while some of them optional. The details of required and optional parameters are given Figure B.2.

| VARIABLE NAME | ARRAY SIZE | DEFINITION | UNITS | DEFAULT |
|---|---|---|---|---|
| XO or X0 | - | Longitudinal coordinate of nose tip | L | 0. |
| TNOSE | - | Type of nose shape:<br>CONICAL or CONE (cone)<br>OGIVE (tangent ogive)*<br>POWER (power law)<br>HAACK (L-V constrained)<br>KARMAN (L-D constrained) | - | OGIVE |
| POWER | - | Exponent, n, for power law shape: $(r/R)=(x/L)^n$ | - | 0. |
| LNOSE | - | Nose length | L | - |
| DNOSE | - | Nose diameter at base | L | 1. |
| BNOSE | - | Nose bluntness radius or radius of truncation | L | 0. |
| TRUNC | - | Truncation flag:<br>.TRUE. if nose is truncated<br>.FALSE. if nose is not truncated | - | .FALSE. |
| LCENTR | - | Centerbody length | L | 0. |
| DCENTR | - | Centerbody diameter at base | L | DNOSE |
| TAFT | - | Type of afterbody shape:<br>CONICAL or CONE (cone)<br>OGIVE (tangent ogive) | - | CONICAL |
| LAFT | - | Afterbody length | L | 0. |
| DAFT | - | Afterbody diameter at base<br>(must be > 0. And not equal to DCENTR) | L | - |
| DEXIT | - | Nozzle diameter for base drag calculation<br>DEXIT not defined gives zero base drag<br>DEXIT = 0. Gives "full" base drag<br>DEXIT= exit gives base drag of annulus around exit only | L | - |
| BASE* | - | Flag for base plume interaction:<br>.TRUE. for plume calculations<br>.FALSE. for no plume calculations | - | .FALSE. |
| BETAN** | - | Nozzle exit angle | deg | - |
| JMACH** | 20*** | Jet Mach number at nozzle exit | - | - |
| PRAT** | 20*** | Jet/freestream static pressure ratio | - | - |
| TRAT** | 20*** | Jet/freestream stagnation temperature ratio | - | - |

Figure B. 2: Required and Optional Parameters for Body of Missile with Datcom




```
CASEID BMOT
DIM M
DERIV DEG
SOSE
PLOT3
DAMP
$REFQ
LREF=0.545,
SREF=0.233,
XCG=0.000,$
$FLTCON
NALPHA=2.,
ALPHA=3.,5.,
NMACH=1.,MACH=5.0,
ALT=0.,$
$AXIBOD
XO=0.,
TNOSE=KARMAN,
LNOSE=1.772,
DNOSE=0.545,
BNOSE=0.052,
LCENTR=5.302,
DCENTR=0.545,
DEXIT=0.0,$
$FINSET1
STA=1.,
SSPAN=0.273,0.725,
XLE= 6.3489,6.4264,
NPANEL=4.,
PHIF=45.000,135.000,225.000,315.000,
CHORD=0.7249,0.6475,
LMAXU=0.1932,0.0849,
LFLATU=0.6135,0.8302,
ZUPPER=0.0251,0.0179,$
$DEFLCT
DELTA1=25.0,-20.0,25.0,-20.0,$ SAVE
NEXT CASE
```

Figure B. 3: An Example of BMOT Input File (for005)