MATHEMATICAL MODEL OF COMBAT AIRCRAFT SIZING & PERFORMANCE OPTIMIZATION

by

PARVATHY RAJENDRAN

Thesis submitted in fulfillment of the requirements
for the degree of
Master of Science

April 2007

ACKNOWLEDGEMENT

I was fortunate to have a unique educational experience in Universiti Sains Malaysia where faculty members constantly discuss the progress and difficulties of their respective field in this project. This environment encouraged much interaction between me and the various faculty members. This experience has done much to further my academic and professional growth.

My main advisor, Prof. Vladmir Zhuravlev was a constant source of advice and encouragement throughout my graduate studies. He has played a key role in my academic development through his numerous information, guidance and motivation through my research work. These experiences have done much to enhance my professional growth and I am grateful for all of Prof. Zhuravlev's efforts.

Also, I am deeply indebted to my co-advisor, Madam Siti Fariza Mohd Dahlan who, on occasions too numerous to count, provided helpful insights into difficulties encountered on issues of computer science especially programming using MALTAB language. Her extraordinary efforts are greatly appreciated.

For the past two years, Mr Illyia Mohd. Yusof, the Dean of Aerospace Engineering, together with Madam Siti Fariza, have made the impossible possible in assisting support for my research project, especially in obtaining access to the restricted high end computing facilities in this university. I'm deeply thankful to both of them as their contribution has made my research into reality.

I would like to extend my utmost gratitude to Dr. Bambang Basuno, for constantly attending to my technical doubts and uncertainties of applied aerodynamics matters arising from this research project. I am also thankful to our technical staffs in School of Aerospace Engineering and Centre of Knowledge, Communication & Technology whom have assisted me in this project.

Finally, I wish to particularly acknowledge three people without whom I certainly would not be writing this today. Foremost, I wish to thank my parents, Mr. Rajendran & Madam Vijayalecthumy, whom inspire me to have constant desire for knowledge. I also wish to express my deepest thanks and love to my husband, Mr. Vigneswara Rao, who has been my best friend, excellent guider and motivator as I progressed through the graduate school. He is truly a remarkable person. It is difficult to express the profound sense of gratitude that I feel towards my family who have been unfailingly supportive throughout my educational career. It is in their love that this work is dedicated.

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PERMODELAN MATEMATIK JET PEJUANG BAGI ANGGARAN BERAT& PENGOPTIMUMAN PRESTASI

ABSTRAK

Tesis ini menerangkan tentang permodelan matematik anggaran berat, prestasi dan pengoptimuman rekabentuk jet pejuang pada tahap konsep awal berasaskan pelbagai kaedah. Model ini dihasilkan khas bagi merekabentuk kapal terbang berinjin kembar yang supersonik untuk operasi “hi-lo-hi”. Selepas kajian terperinci, anggaran mengenai berat kapal terbang, aerodinamik dan pendorongnya dilakukan. Kemudian, proses menganalisis prestasi penerbangan dilakukan untuk memenuhi keperluan rekabentuk yang telah dibentangkan. Akhirnya, pengoptimuman rekabentuk dilakukan untuk menghasilkan rekabentuk yang paling ringan ataupun paling menjimatkan kos. Permodelan matematik ini direalisasikan sebagai sebuah atur cara komputer bagi memudahkan analisa. Pengesahan model ini dilakukan dengan membuat perbandingan keputusan analisa komputer dengan nilai bagi 10 kapal tempur yang terdapat di pasaran. Keputusan pengesahan menunjukan peratusan perbezaan data adalah kurang 10% bagi kebanyakkan parameter seperti yang dicadangkan bagi tahap rekabentuk yang dijalankan. Maka, model ini boleh digunakan sebagai alternatif bagi menjalankan anggaran berat, prestasi dan pengoptimuman rekabentuk kapal terbang tempur. Sebuah kajian kes dilakukan menggunakan model ini, diikuti dengan contoh pengiraan langkah demi langkah bagi satu rekabentuk boleh laksana. Beberapa cadangan untuk kajian lanjutan tesis ini turut disertakan.

MATHEMATICAL MODEL OF COMBAT AIRCRAFT SIZING & PERFORMANCE OPTIMIZATION

ABSTRACT

This thesis gives thorough analysis on the mathematical model of combat aircraft sizing, performance and optimization for initial conceptual design stage, based on various fighter design methodology. The developed mathematical model is specifically for designing a supersonic fighter of twin engine aircraft where the design mission of this fighter is hi-lo-hi operation. After a comprehensive literature study, an initial estimation of weight, aerodynamic and propulsion is performed. Then, the process continues with aircraft sizing to meet the performance requirement. In addition, optimization techniques are used to obtain the lightest or lowest cost aircraft that meet both design specification and performance requirement. The model is transformed to a program using MATLAB language for computational analysis. The model is validated by comparing results of computational analysis against real data of ten (10) fighters. The validation results of this model have shown a good agreement where they meet the requirement of below 10% of error for the conceptual design level, for most of the parameters analyzed. Therefore, this model may be used as an alternative method to perform initial sizing, performance and optimization of a fighter design. A case study is conducted using this model, followed by a step-by-step example of initial conceptual design calculation of one feasible design. Suggestions on future works are also presented.

Chapter 1

Introduction

1.1 PREFACE

Aircraft design is a discipline of aeronautical engineering; different from the analytical disciplines such as aerodynamics, structures, controls and propulsion. An aircraft designer needs to be well versed in these and many other specialities to be able to create the geometric description of the aircraft to be built.

Aircraft design is not just the actual layout, but also the analytical processes used to determine what should be designed and how the design should be modified to meet the desired requirements (*Raymer, 1999*). In fact, Raj (1998) and Raymer (1999) agrees that design is an iterative process of requirement, design concept, design analysis, sizing and trade studies; as shown in figure 1.1 below.

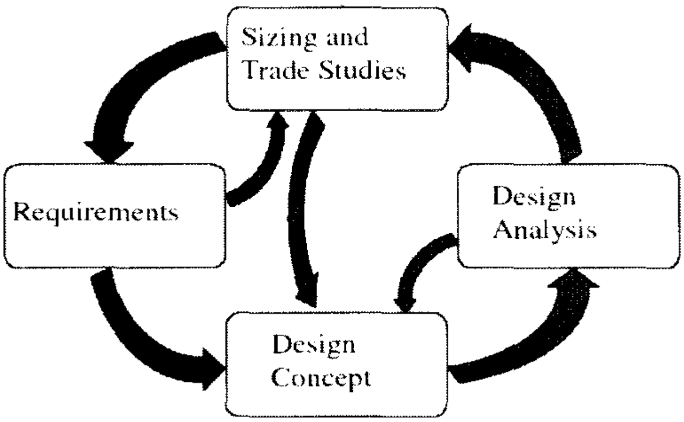

Figure 1.1 : The Design Wheel (*Source: Raymer, 1999*)

Basically, there are three major phases of aircraft design widely agreed by aircraft designers; conceptual design followed by preliminary design and then the detail design as in figure 1.3. As the process go through the phases of design, the level of detail of the design steadily increases.

Besides that, an aircraft has to go through numerous wind tunnel testing and simulation, then followed by prototype manufacturing, and finally goes through a successfully flight test to be able to manufacture a particular design for production. However, only the description of conceptual design is elaborated throughout the thesis.

The conceptual design may be divided into two parts. The first part includes obtaining a set of design requirements, studies of technology availability, creating an innovated design into conceptual sketch (optional), first guess sizing, analyzing the initial weights, propulsions and aerodynamics, and finally, optimizing the sized the aircraft to meet the performance. The second part of conceptual design will be analysis in the field of configuration, drag polar, weights & balance, stability & control, structures, cost and subsystems as shown in figure 1.2 below.

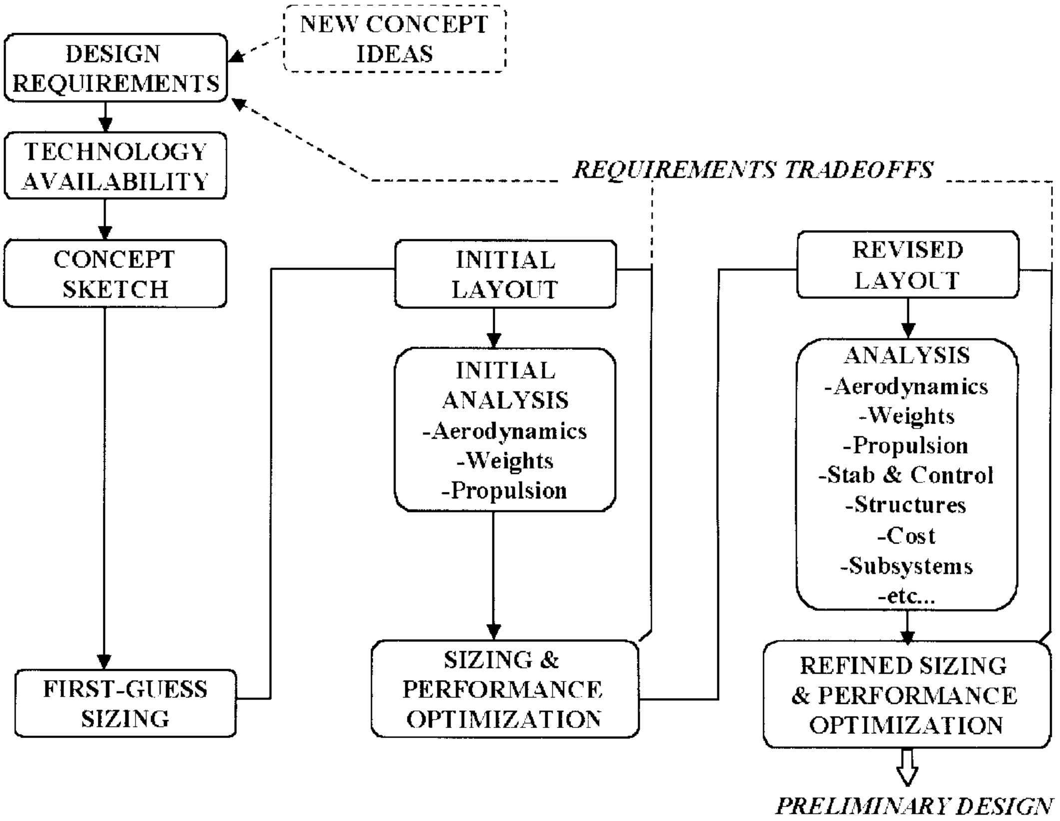

Figure 1.2: Aircraft Conceptual Design Process (*Source: Raymer, 1999*)

Usually, the conceptual stage requires a staff of 15 - 30 people, over a period of 1 - 2 years and the cost roughly ranges of 6 - 12 million dollars (*Jameson, 2003*). Thus, this thesis only considered the initial conceptual design stage (which is the first part of conceptual design) and there are no detail studies of the configuration, drag polar, weight & balance, stability & control, structure or the cost of the aircraft given.

Therefore, this thesis entitled, “Mathematical Model of Combat Aircraft Sizing & Performance Optimization”, is to develop a mathematical model for initial conceptual design of supersonic fighter specifically twin engine aircraft. The design methodology developed uses concepts, guidance and references of various aircraft designers. Some of the main references in accomplishing the project are “Airplane Design I” by Dr. Jan Roskam, “Aircraft Design: A Conceptual Approach” by Daniel P. Raymer and “Synthesis of Subsonic Airplane Design” by Torenbeek. Other references that are also referred throughout the thesis are listed in References.

The mathematical model is a mathematical representation of a process, device, or concept by means of a number of variables which are defined to represent the inputs, outputs, and internal states of the device or process, and a set of equations and inequalities describing the interaction of these variables. Thus, this thesis presents the development of mathematical model which comprises initial conceptual design process of aircraft sizing, performance and optimization of fighter based on various design methodology.

Moreover, a mathematical model serves the following purposes: (1) to establish understandings of the relationships among the input data items within a model; (2) to answer a variety of what-if questions; (3) to attempt to extrapolate past data to derive meaning; and (4) to find an optimal solution to a planning or decision problem.

At first, to create understandings of the relationships among the input data of the model, a specific set of design requirements without any conceptual sketch is outlined. Since, the establishment of fixed, firm or intuitive requirements immediately reduces the options for design (see the design freedom curve in figure 1.3), a sensible selection of applicable design requirements have been carried out based on the availability of technology. This is characterized as parametric studies, which need to be performed quickly, at relatively low cost, and with good accuracy (*Sanghi, 2002*).

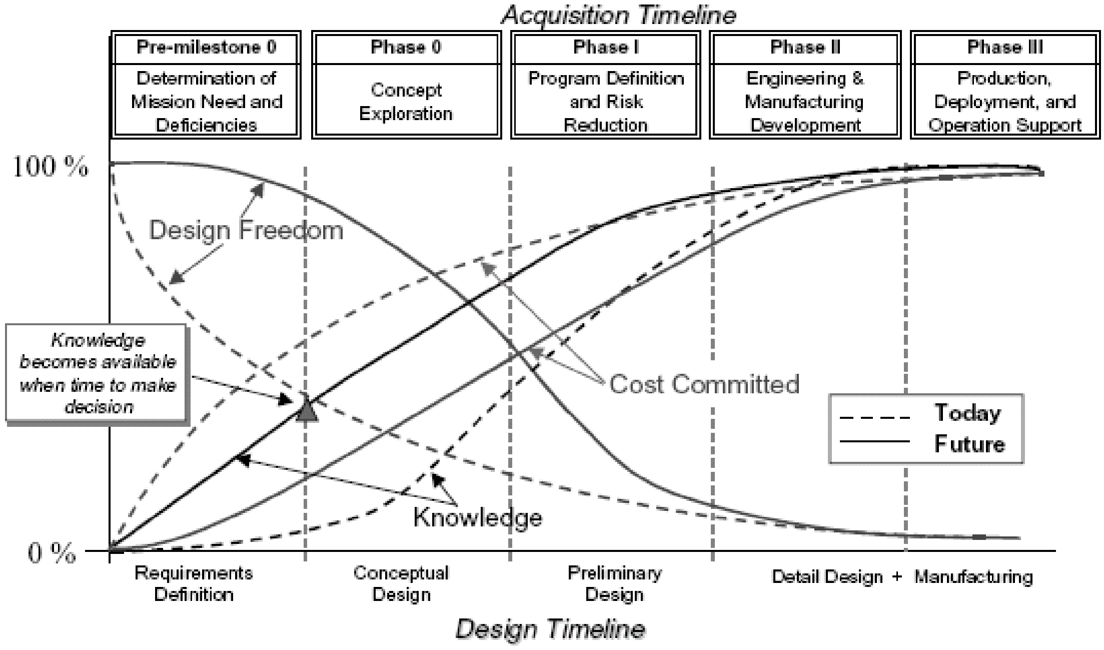

Figure 1.3 : The Relationship of Design Freedom, Knowledge & Cost Committed. (*Source: Mavris, 2000*)

After the parametric studies, an initial estimation of weight, aerodynamic and propulsion is performed. Then, the process continues with sizing the aircraft to meet the performance requirement. Finally, to find an optimal solution, optimization techniques are used to obtain the lightest or lowest cost aircraft that meet both design specification and performance requirement (*Anderson, 1999 & Raymer, 1999*).

Moreover, designing a complex technical system in present-day conditions is impossible without the use of optimization techniques. The rise of the complexity of systems, as well as the number of parameters needed to be coordinated with each other in an optimal way, have led to the necessity of using mathematical modelling and application of optimization techniques (*Igor, 2004*).

In addition, mathematical models usually include techniques such as Linear Programming computer simulation, Decision Theory, Regression Analysis, Economic Order Quantity (EOQ) and Break-Even Analysis. If the operators, objective functions and constraints are represented entirely by linear equations, then the model is regarded as a linear model.

However, this project has developed a mathematical model which applies numerical techniques which then is transformed into programming model. This programming model is defined as the minimization or maximization of a function subject to inequality constraints expressed in '≤' form as discussed by *Arora, 1992 & Przemieniecki, 2000*. Moreover, it is worth noting that the algorithm of this mathematical model has thirteen (13) constraints to satisfy the design problem. In fact, any realistic design problem usually contains numerous constraint analyses (*Mason, 1998*).

Cramer (1995) expressed the importance of computational analysis since the industry has asked universities to increase more design training for engineers, to design and bulid computer program. MATLAB 2006a has been chosen as the programming language for linear programming model because it is a very powerful application for solving most engineering problems. MATLAB stands for Matrix Laboratory, because its basic data element is a matrix (array). It is a very popular language for technical computing used by students, engineers, and scientists in universities, research instituted and industries all over the world (*Glaze, 1998 & Gilat, 2004).*

1.2 OBJECTIVE

The aim of this project will be the following aspects of objective and goal as mentioned below:-

1. To study the basic theory in designing a conceptual aircraft, by carrying out the initial design parameters approximation of the to-be-designed aircraft.
2. To develop the mathematical model of aircraft sizing, performance and optimization of fighter based on various design methodology.
3. To develop the computer code using the mathematical model described to carry out fighter aircraft sizing, performance analysis and optimization.

1.3 PROBLEM STATEMENT

The main motive to develop this mathematical model is to be able to design an aircraft without the use of any aircraft design software available in the market. Generally, aircraft design software is expensive. The capabilities of the design software are limited to conventional aircraft designs. Many parameters such as angle of attack, swept angle, turn rate and pitch rate are fixed to a set of range defined by the software developer. The design methodology and the source code used are the most crucial information of any design software is confidential. Thus, a developing nation like Malaysia requires skills in aircraft design to be able to design and manufacture our own aircrafts. Moreover, the author believes the nation’s priority will be on defence support.

Therefore, a project to study the basic theory in designing a conceptual aircraft has being carried out. The thesis has produced the design methodology of fighter aircraft specifically in initial sizing, performance analysis and optimization, based on various fighter design methodology available. A computer program (design software) is also produced to pre-select the design point and importantly to eliminate the time taken for decision making of problems for desired result. Eventually, moving to the next stage of aircraft design process can be achieved in ahead of time.

1.4 LAYOUT OF THESIS

A general introduction is presented in this current chapter and it has provided the preview, the objective, and also the problem statement of this research project. A comprehensive literature survey is presented in chapter two, to review the previous computational and analytical work in the field of combat aircraft.

Chapter three details the combat aircraft design methodology. Throughout this chapter, the descriptions of the design procedure for fighter aircraft sizing, performance and optimization are given. This includes full descriptions of equations used in the design procedure and also the important parameters are introduced intensively.

The fourth chapter explains on the flow of the mathematical model developed by providing the variables, assumptions and constants, and technical requirements used in the program. It is also found that some parameters in the method have to be assumed because there are no experimental or computational results available. The differences between the validation and case study work performed using this mathematical model are also introduced. This chapter will also include the flow chart and the description of the programming process.

Chapter five presents validation of the model by providing the comparison of computational results and real data of ten (10) fighter aircrafts. Then, the results of case study are discussed after an example of step-by-step initial conceptual design calculation of one feasible design obtained from the case study. Finally, chapter six contains conclusions made based on the results with some suggestions and ideas for further research work.

Chapter 2

Literature Review

2.1 PREFACE

Aircraft design is a multidisciplinary integration job in design and engineering of the best available or urgently required technologies to meet not only the customer and market requirements but also the target cost issues that demand a dramatic change in skills of not only design engineers but also project and line management (*Schmidt, 2001*). In the past, the military air combat industry has achieved significant advances in technology. This includes improvement in the standards of speed, reliability and safety while costs in real terms have been reduced.

Nevertheless, the design of a supersonic combat aircraft and the procedures involved in flying an aircraft from a military base to another or land in the home base, are truly complex. These design and flight methods require a great deal of knowledge, skill, experience and training. But then, many resources, books and references are not available for public. Apart from aircrafts data, many procedures and methods are also not accessible by civilians.

In general, processes of designing an aircraft are accomplished by a combination of theoretical, experimental and computational techniques. Spurred by the decrease in computing costs relative to other costs including wind tunnel and flight test, a continually enlarging fraction of mission analyses rely on computation. The increase in computational work in an aircraft design has become more obvious when NASA has designed preliminary design methods, principally using linear methods with nonlinear corrections (*Alexandrov, 2002*).

Therefore, in sub-chapter 2.2, 2.3 and 2.4, there will be discussions related to the history of fixed wing military aircraft industry development, followed by the military aircraft specification and operation. The studies on these topics give an up-to-date trend of performance capabilities and technology development. Most importantly, it gives an idea/suggestion of the expected future design for military operation.

Besides identifying technology availability and its development, technical aspect related to aircraft design are reviewed in sub-chapter 2.5, 2.6 and 2.7. They are the aircraft aerodynamics, propulsion and cost parameter dependency on designing an aircraft. These are crucial studies since defining aircraft aerodynamics of a real aircraft is more complex than theoretical definition. The aircraft propulsion and cost limitation will define the large bottleneck associated in designing a new aircraft.

Finally, in sub-chapter 2.8, 2.9 and 2.10, the aircraft's computational design, optimization effort and marketed aircraft design software are discussed in detail. Time reduction of design and it's related to cost saving with improved data can easily be incorporated in a computerized system. Therefore, efforts of computational work are elaborated in these sub-chapters to improvise or at least to prevent unnecessary duplication the available system/ software.

2.2 AIRCRAFT INDUSTRY DEVELOPMENT

Examining the history of fixed wing military aircraft development, five distinct technology eras can be identified, as shown in table 2.1 below. They are the Biplane era (1909-1931), the propeller era (1931-1945), the subsonic jet era (1945-1953) the supersonic jet era (1953-1981), and the stealth era (1981-present) (*Shiue, 2005*).

Table 2.1: Era of Aircraft Development (*Source: Shiue, 2005*)

Era	**Innovation Periods**
Biplane	1909 – 1931
Prop Monoplane	1931 – 1945
Subsonic Jet	1945 – 1953
Supersonic Jet	1953 – 1981
Stealth	1981 - Present

2.2.1 The Biplane Era (1909-1931)

The rapid decline in military demands post World War I in 1918 had a devastating effect on the aircraft industry. In 1917, U.S. military aircraft production had jumped 400 percent, from the production total of just over 400 the preceding year to over 2,000 aircrafts. In 1918, total military aircraft production exploded to over 14,000, and then was slashed in 1919 to fewer than 800 aircrafts. By 1922, annual production had plunged to 263. Figure 2.1 clearly show the military procurement was the backbone of the industry, although small and uncertain as it is (*Shiue, 2005*).

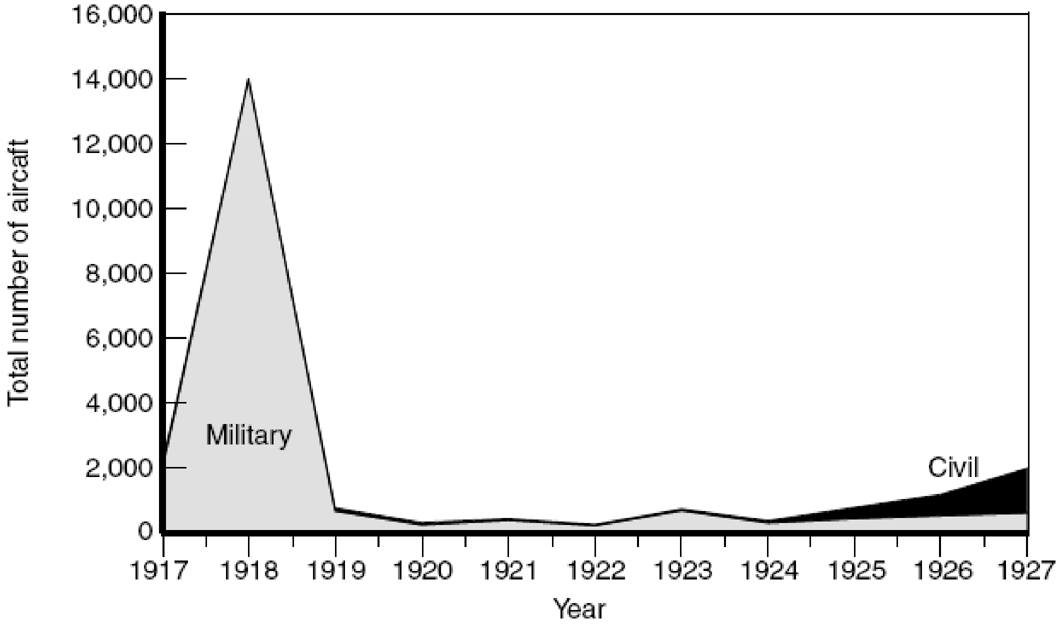

Figure 2.1: U.S. Aircraft Production from 1917-1927 (*Source: Shiue, 2005*)

2.2.2 Monoplane Propeller Era (1931-1945)

The birth of the commercial airline industry in the early 1930s created a demand for a new generation of high-performance passenger transport aircraft. The growth in the commercial market was stimulated by the Waters Act of 1930. The Waters Act of 1930 reduced the government subsidies for airmail that provided the main source of profits for the fledgling commercial airlines. Figure 2.2 below clearly show the military and civil production from 1928 – 1938 (*Shiue, 2005*).

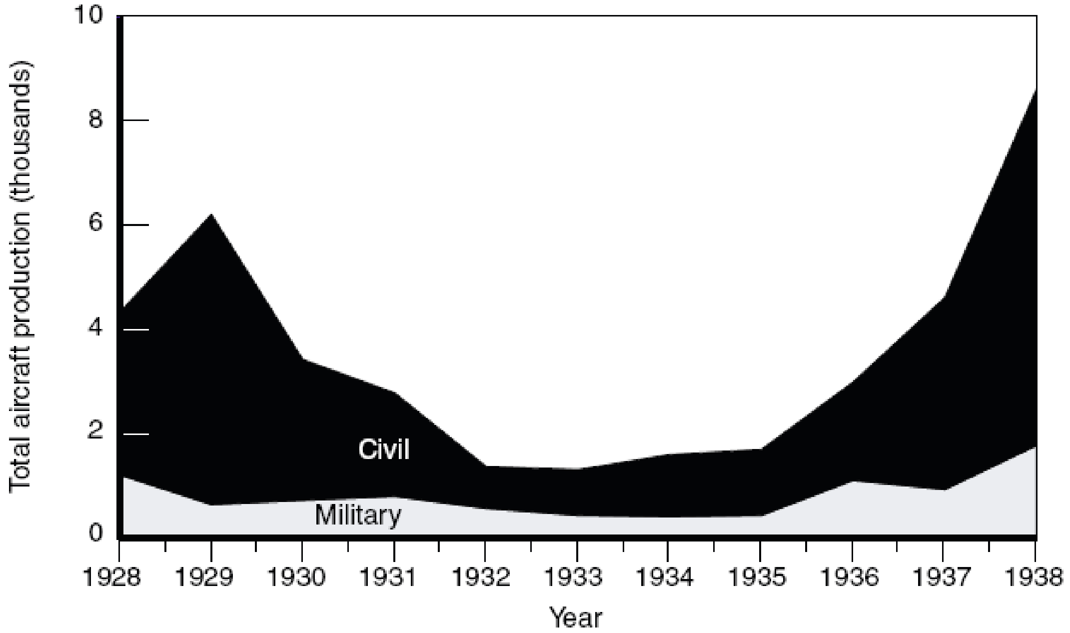

Figure 2.2: Military & Civil Aircraft Production from 1928-1938 (*Source: Shiue, 2005*)

2.2.3 The Subsonic Jet Era (1945–1953)

The period from 1942 through 1947 is characterized by rapid and dramatic technological advancement. Companies exploited the enormous increases in performance made possible by the jet engine. This ultimately led to revolutionary advances in combat aircraft performance. As seen in Figure 2.3, numerous companies competed for the available aircraft development (*Murman, 2000 & Shiue, 2005*).

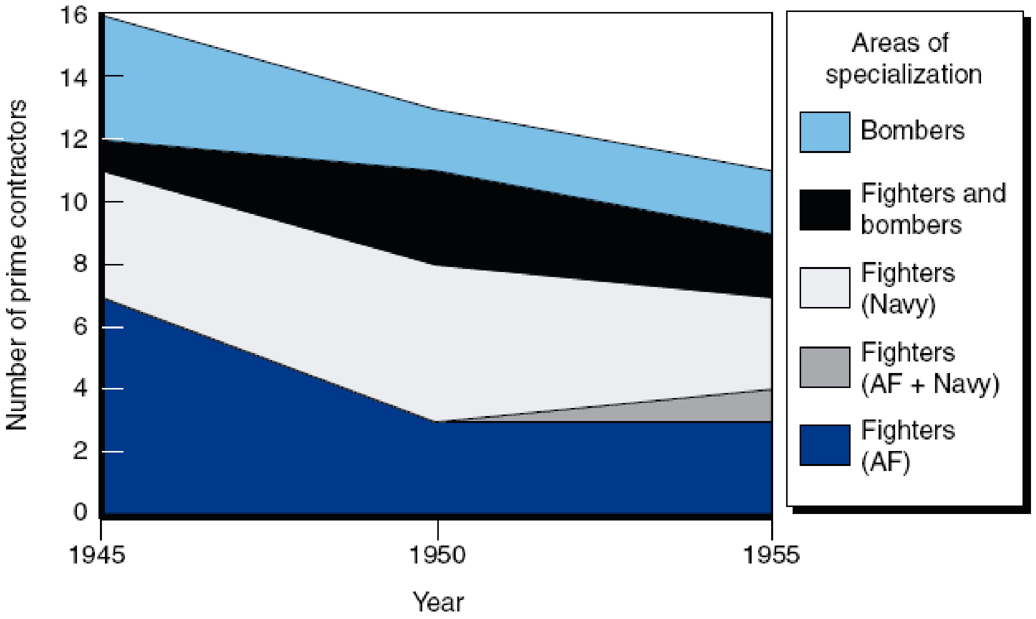

Figure 2.3: Military Aircraft Contractors from 1945 - 1955 (*Source: Shiue, 2005*)

2.2.4 The Supersonic Jet Era (1953–1981)

By the early 1950s, there are large advances in jet-turbine engine power and efficiency. The arrival of the afterburner and resolution of the basic aerodynamic design problems for high-speed flight, led to an explosion in aircraft speed and altitude capabilities. The technological focus on increasing speed and ceiling in the 1950s was replaced by a focus on maneuverability and systems integration (*Shiue, 2005*).

2.2.5 The Agile Supersonic – Jet Revolution (1972–1981)

Subsequently, the aerospace field was challenged to produce products and systems of "Better, Faster, and Cheaper". This new paradigm is a considerable change from the mantra of "Higher, Faster, and Farther" that had been the driving force behind aerospace products and systems for many years (*Murman, 2000*).

The late 1960s and 1970s witnessed the development of two new Air Force fighters, the F-15 and F-16, and two new Navy fighters, the F-14 and F/A-18. These four fighters become the mainstays of U.S. fighter forces till the end of the 1990s. The period from the early supersonic-jet revolution through the agile supersonic-jet revolution exhibited continuous and tough competition among eight or more credible contractors for the small number of new tactical combat aircraft and bomber programs as shown in figure 2.4 below (*Shiue, 2005*).

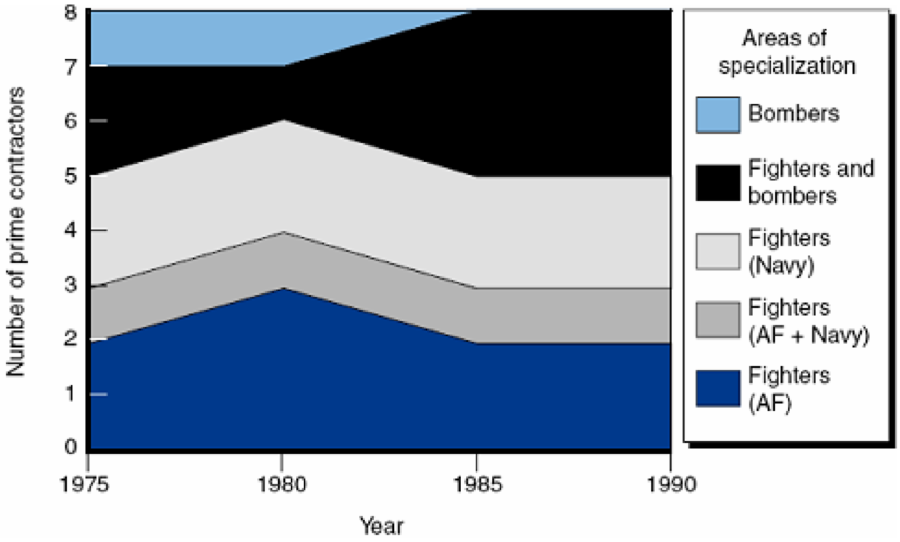

Figure 2.4: Aircraft Company & Specializations in 1980s (*Source: Shiue, 2005*)

2.2.6 Stealth Era (1981-Present)

In early 1993, Lockheed purchased General Dynamics' Fort Worth fighter division. In mid-1994, Lockheed and Martin-Marietta agreed to merge, adopting the new name of Lockheed-Martin. In April 1994, Northrop purchased Grumman, ending the independent existence of the company that had been the Navy's premier fighter developer since the mid-1930s. In 1996, Boeing bought Rockwell's aerospace and defense divisions, North American–Rockwell. Boeing followed this move almost immediately by announcing an even bigger move, a merger with its long-time rival, McDonnell-Douglas (*Shiue, 2005*).

Thus, in just over four years, four historical leaders in fighter R&D appeared to have been eliminated as independent entities: General Dynamics, Grumman, McDonnell-Douglas, and Rockwell. The number of prime contractors in US with credible capabilities to develop new combat aircraft had been reduced from eight to just three: Lockheed-Martin, Northrop, and Boeing (*Shiue, 2005*).

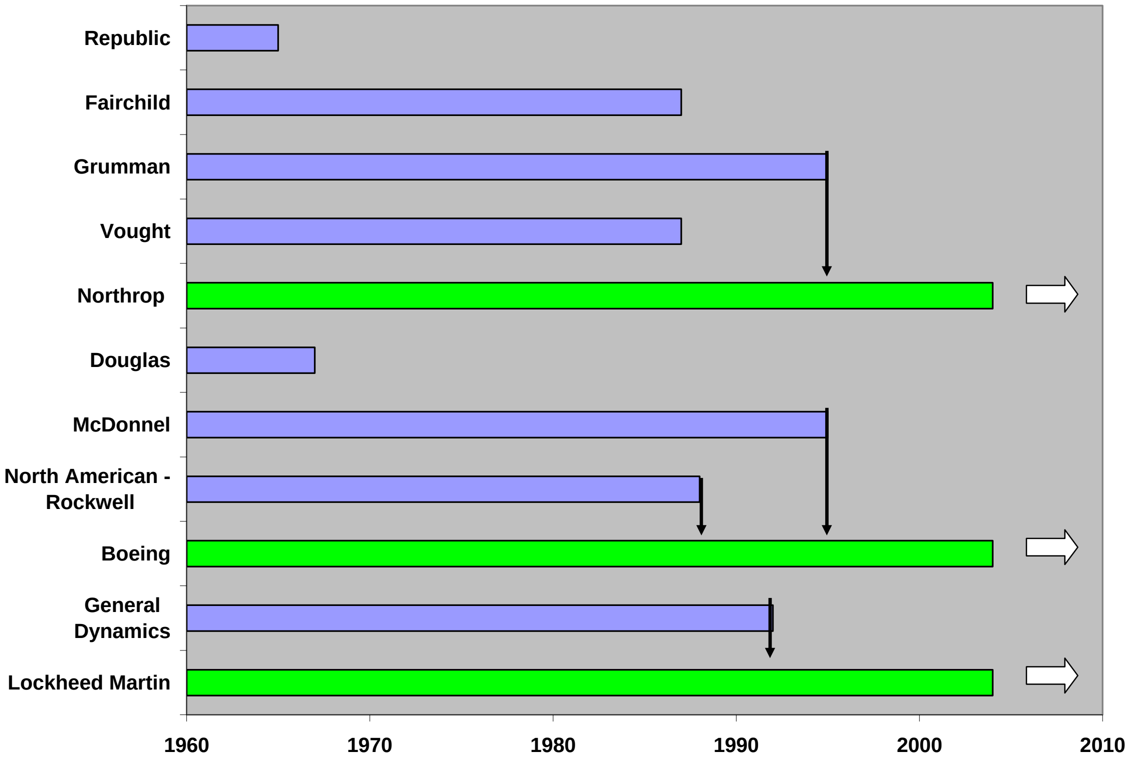

Figure 2.5: US Military Aircraft Prime Contractor, 1960-Present (*Source: Shiue, 2005*)

Merging of defense contractors has raised the fear that the lack of competition will suppress innovation. In the 1950s, there are eleven prime contractors competed for aircraft contracts but by 1990 only eight firms survived and in 2001, only three companies, Boeing, Northrop-Grumman, and Lockheed, are capable of designing and producing advanced military aircrafts as shown in figure 2.5 (*Shiue, 2005*).

This issue crystallized in the fall of 2001 when Lockheed Martin (with Northrop Grumman as a subcontractor) was selected as the winner of the F-35 Joint Strike Fighter competition and as the sole prime contractor to develop and manufacture the F-35, Boeing became the loser of the competition is faced with end of its military aircraft program after completion of its current F-15 and F/A-18 programs (*Shiue, 2005*).

This situation has been partially caused by the rationalization and concentration process of the aerospace industry and partially by the lack of the willing military customers due to severe cuts in defence budgets. The airplane industry is more and more forced to design for the customer values like key buying factors derived from the whole life or service cycle of the airplane rather than just performance (*Schmidt, 2001*).

However, the current "crisis" in aeronautics shows both a unique development and a continuation of designer's cyclical past. The need for an aggressive means to replenish and sustain the pool of airplane design talent needed to maintain an industry that continues to find a multi-billion dollar a year market for its products. The present pool is ageing and being drained by retirement, and its replacement faces increasingly severe competition for both young and experienced talents (*McMasters, 2001 & 2002*).

Nevertheless, the aviation program in US with the highest cumulative procurement value through fiscal 2006 is the USAF's F/A-22 Raptor, leading the pack at nearly $23 billion. As in 2004, its producer Lockheed Martin is currently under contract for 52 aircrafts and the USAF has earmarked approximately $42 billion to purchase 276 F/A-22s through 2011 (*Bellizan, 2004*).

As for Russian fighter aircraft industry, the main fighter aircraft design and manufacturing enterprises in Russia are Sukhoi and Mikoyan. They mainly dependent on their fighter aircrafts export, due to insufficient of internal demand for fighter aircrafts. This also has lead to a discussion of merging the two companies to form "Joint Aviation Corporation" in year to come (*Schwarzler, 2000 & Zhuravlev, 2006*).

As a summary of aircraft development, the Cold War era vision: "farther, faster, higher" are being replacement with the "faster, higher, farther, cheaper, better, quicker, cleaner, quieter and safer.", or simply "leaner, meaner, greener" (*McMasters, 2003*).

2.3 MILITARY AIRCRAFT SPECIFICATION

There are many types and definitions of military aircrafts designation over the years; fighter/ground attack, bomber, reconnaissance, trainer, tanker, military cargo and/or combinations of any of these aircrafts (*Roskam, 1997 & Fielding, 1999*). Today, aircraft manufacturers tend to design planes with multi-role abilities, with both bomber and fighter qualities.

The original concept of the fighter was to be used for intercepting and dog-fighting with enemy fighters. The first specialization of role was the development of 'interceptor' fighters designed for the sole purpose of destroying enemy bombers. Then came the use of fighters for ground-attack work, using guns and rockets, and it was then only a short step to fighter/strike aircraft carrying bombs and fighter/reconnaissance carrying cameras and specially trained sharp-eyed pilots.

Generally, fighters are fast, highly maneuverable, and capable of destroying enemy aircraft and ground targets. Their main purpose is air-to-air combat, offensive or defensive. Escorting bombers or other non-attack aircraft is also a common task. They are capable of carrying a large number of weapons, including machine guns, cannons, rockets, guided missiles, and bombs, depending on the mission.

In fact, the interceptors are the specialized fighters. The interceptor is a fighter with a particular fast climb with high-level performance but has insufficient fuel for a longer range than a fighter. The ordinary fighter climbs more slowly, because it must carry additional fuel in overload tanks to be able to loiter or fly longer distances to its quarry that makes it a lower level in performance (*Stinton, 1998*).

Bombers are typically larger, heavier, and less maneuverable than fighter aircraft. They are capable of carrying large amount of weapons. They are used for attacks on the ground and usually not fast or agile enough to take on enemy fighters. Most require at least two crew members to operate. Some bombers have stealth capabilities that keep them from being detected by enemy radar.

Reconnaissance aircraft are primarily used to gather intelligence. They are equipped with photographic, infrared, radar, and television sensors. This aircraft may be specially designed or may be modified from a basic fighter or bomber type. Some are equipped with special electronic gear for detecting submarines, such as sonar, and others can give early warnings of enemy approach.

Military cargo aircraft are primarily used to transport troops and war supplies. They can be attached to pallets, which are easily loaded, secured for flight, and quickly unloaded for delivery. Cargo also may be discharged from flying aircraft on parachutes, eliminating the need for landing. The aerial tanker can refuel fighters, bombers, and helicopters while in flight. This means that an aircraft can go to any point on the globe without landing even once.

These military aircraft specifications are often derived using operational research techniques, but also include significant input from pilots and engineers. They rely heavily on data from existing aircraft especially when this aircraft need to be replaced or to be improved by other aircraft. The perceived threat is an important element of the specification and is determined from intelligence sources (*Fielding, 1999*).

2.4 MILITARY OPERATION

Scientific methods of analysis play an increasing significant role in planning military operations and determining optimal use of the available defence forces to ensure national security. These methods provide a rational approach for exploring different alternatives for force deployment and for determining the best strategies and tactics in actual combat engagements (*Przemieniecki, 2000*).

The importance in the military operation analysis are given in the usage of weapon systems, management of weapon system resources, human factors in weapon systems, weapon system life cycle cost, fundamental of offence and defence, factor affecting target selection, target coverage and damage, target search strategies, target hit probabilities, vulnerability, reliability and availability of systems, maneuverability, agility, cost analysis, survivability, and countermeasures (*Przemieniecki, 2000*).

In an aircraft operation, the types of weapons commonly used for combat engagements are guns, bombs, rockets and missiles. The rotary 'Gatling' or gas operating revolvers are two types of guns commonly used for battles. There are conventional free fall bombs, retarded bombs, cluster bombs and laser guided bombs to select from. As for the missiles, there are air-to-air and air-to-ground missiles.

2.5 AIRCRAFT AERODYNAMICS

The principle focus of aerodynamic is fluids in motion. Hence, flow velocity is an extremely important consideration. This study of aerodynamics has evolved into a study of numerous and distinct types of flow, especially in the field of continuity, viscosity, compressibility and velocity.

The continuum flows happens when the molecules impact the surface body so frequently that the body cannot distinguish the individual molecular collision and the surface feels the fluids as a continues medium, whereas the verse of such flow is called free flow molecular.

However, free molecular flows are just a small part of the total spectrum of aerodynamics. A flow that is assumed to involve in friction (viscosity), thermal conduction or diffusion is called viscous flows, whereas, the inviscid flow exhibits the contrast phenomena of viscous flow, do not truly exist in nature (*Anderson, 2001*).

The consideration of the nature of flow density is known as compressibility. A flow in which the density is constant is called incompressible flow; in contrast, a flow where the density is variable is called compressible flow. Although in nature the density will not be constant, it is assumed that the incompressible flow has a negligible actual density variation. Thus, *Anderson, 2000 & Brandt, 2003* have stated that it is safe to assume that the flow is incompressible at Mach number below 0.3.

Of all the ways of subdividing and describing different aerodynamic flows, the characteristic based on the Mach number is probably the most prevalent. The four Mach number regimes can be identified as subsonic, transonic, supersonic and hypersonic regimes. The may be expressed in terms of speed as Subsonic flow : $M < 0.8$, Transonic flow: $0.8 < M < 1.2$, Supersonic flow: $1.2 < M < 5.0$ and Hypersonic flow: $M > 5.0$ (*Anderson, 2001*). However, Mason (2005) has suggested the transonic flow regime that ranges from Mach number 0.6 or 0.7 till 1.2.

2.6 AIRCRAFT PROPULSION

Aircraft propulsion systems are classified as air-breathers, where they use the oxygen from the atmosphere to burn with a petroleum product fuel. The four types of aircraft propulsion systems to be considered for aircraft design are the pure turbojet, the reciprocating engine and propeller combination (the piston-prop), the turboprop and the turbofan (*Hale, 1984*). In addition to these air-breathing propulsions system, ramjet engines are also used for aircrafts flying at Mach number more than two (*Fielding, 1999*). In modern generation of fighters see a trend of using on pure turbojet and turbofan engines with the capability of reheat (also known as afterburner).

In long range aircrafts, the fuel weight may be four times the weight of the payload. At the same time, the engines in these aircraft themselves weigh more than 40% of the payload. When an aircraft is expected to execute strenuous maneuvers or achieve high acceleration rates, especially fighters, more than 15% of the maximum take-off weight are contribution of the engines weight. Thus, in practice, designers exploit improvements in engine effectiveness in various ways to optimize the value of design (*Oates, 1989*).

2.7 AIRCRAFT COSTS

All aircraft represent an investment of money for an anticipated profit. Although the revenue derived from investment is less tangible for many military aircraft, these too are expressed to provide some kind of an identifiable payoff that can be expressed in terms of money. Since aircraft size has a very profound effect on cost, appropriate economic analysis is crucial and always precedes a decision to design, develop and manufacture a new or a modified type of aircraft engine (*Oates, 1989*).

However, in the 1950s and 60s, aircraft performance requirements were often the primary design drivers, especially for military aircraft, and higher than planned costs were often accepted by customers in order to get the performance they desired. In the present day, cost is far more important to customers, and performance requirements are frequently revised in order to allow a new aircraft design to meet its cost goal (*Brandt, 2003*).

The acquisition costs are the cost of buying or acquiring the aircraft which includes both operating and life-cycle costs. The reasons for high aircraft acquisition costs are (*Fielding, 1999 & Kirby, 1999*):-

- High performance requirements
- Safety considerations
- Quality control

- Tooling requirements
- Labour intensive production
- Large financial investment
- Large interest cost
- Short production runs

Both Torenbeek (1982) and Hale (1984) expressed that the weight is a crucial consideration in the performance and design of an aircraft. Their design experiences have shown that the lowest weight design is also the cheapest and most efficient design. Every extra pound of weight is accompanied by an increase in the wing area, thrust, fuel, etc., all leading to a further increase in the aircraft weight and adversely affecting the performance and costs (both initial and operational) of the aircraft.

Modern developments in materials and fabrication technology have made it possible to build structures which are significantly lighter. This also saves on the costs of the components. The new materials are mostly composites that are made up of two or more materials such as fiberglass cloth and epoxy resin.

At present, because industry is still learning how to use advanced materials, the presence of such materials in an aircraft structure may save from 0-10% of the structural weight and not save at all on cost. There is good reason to expect that when this design and fabrication technology is mature, it will save 20% or more on structural weight and as much as 50% on the cost of some components. However, the full benefit of this technology has yet to be applied to aircraft design and construction (*Brandt, 2003*).

The arrival of various computer design tools such as design analysis programs, computational fluid dynamic modelling, flight simulation modelling and integrated computer aided design and manufacture systems (CAD/CAM); has gone some way to reducing the above problems, particularly in reducing development times and improving initial build quality.

In addition to these cost reduction, an impressive progress has been made in development and manufacturing of aerospace systems with the application of lean over the last decade. The impact of applying lean manufacturing to the design process of approving drawing releases for an aircraft program shows, the number of signatures required was reduced by 63%, the rework of release engineering was reduced from 66% to 3%, and total cycle time for drawing releases was reduced by 73%. However, in terms of cost, there was only 6% reduction (*Murman, 2000*).

2.8 COMPUTATIONAL AIRCRAFT DESIGN

In aircraft design, the necessity of a considerable amount of computational work leads to computerized design studies as a prerequisite for advanced and complex aircraft. However, the system must be developed, monitored and utilized by experienced designers in order to define the design problems and interfaces between various technical disciplines in the design, to prevent unrealistic results.

The validity of computerized studies is determined entirely by the accuracy of the input data and design methods available. In that case, they are no better than manual computations. However, time reduction of design and it's related to cost saving with improved data can easily be incorporated in a computerized system. The following design goals can be achieved with a computerized system (*Torenbeek, 1982*):-

- Determination of combinations of parameters, characterizing designs that satisfy specified operational requirements.
- Calculation of values for the configuration parameters resulting in the most favourable objective function.
- Sensitivity studies to assess the effect of minor changes in the shape or geometry, material properties, drag coefficients, etc.
- Mission/performance analysis and trade-off studies to investigate the effect of variations in the performance requirements.
- The effect of certain technological constraints in terms of weight and cost.

Although, computational methods began as early as 1965, only in the last two decades, aerodynamics and Computational Fluid Dynamics (CFD) have played an increasingly vital role in the design methodology and actual development process for modern aircraft. None of the latest developments in any area of air vehicles has been done without substantial contributions from CFD to design better products at lower cost and risk (*Jameson, 1997, 2003, Schmidt, 2001 & Johnson, 2003*).

Furthermore, CFD has to be applied as early as possible in the conceptual and preliminary design stages, when design freedom exists at low cost concerning changes with regard to the systems concept. The conceptual design stage is the point where the most freedom is available to change the design, thereby allowing CFD to make the largest impact. But then, advanced CFD tools aren’t used until the start of preliminary design at the earliest due to requirements of High End Computing facilities (Mason, 1998 & Schmidt, 2001).

The presents of High-End Computing facilities satisfy the most demanding scientific goals, to push the boundaries of researchers’ ambitions and also stimulate the development of hardware and software technologies. Today, many applications codes can effectively exploit around 1000 processors. Raising this limit by one or more factors of 10 is an active area of research & development. For truly large systems, this has caused difficulties in running large jobs with long execution times (*Cant, 2004*).

Even though there has been significant progress in the speed of a single processor in the last decade, it still does not provide enough computational resources to cater to the demands. Therefore, to solve large-scale problems, parallel computing is often resorted to. Generally, parallel computing is based on distributed load and shared memory. While a shared memory environment provides ease of implementation of algorithms, a distributed parallel computing platform promises higher scalability at the expense of increased implementation complexities (*Sanjay, 2004*).