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PRELIMINARY DESIGN AND PERFORMANCE ANALYSIS OF THE TURBOSHAFT ENGINE

A Thesis Submitted in Partial Fulfillment for the Requirements of the degree of B.SC (honors) in Aeronautical Engineering

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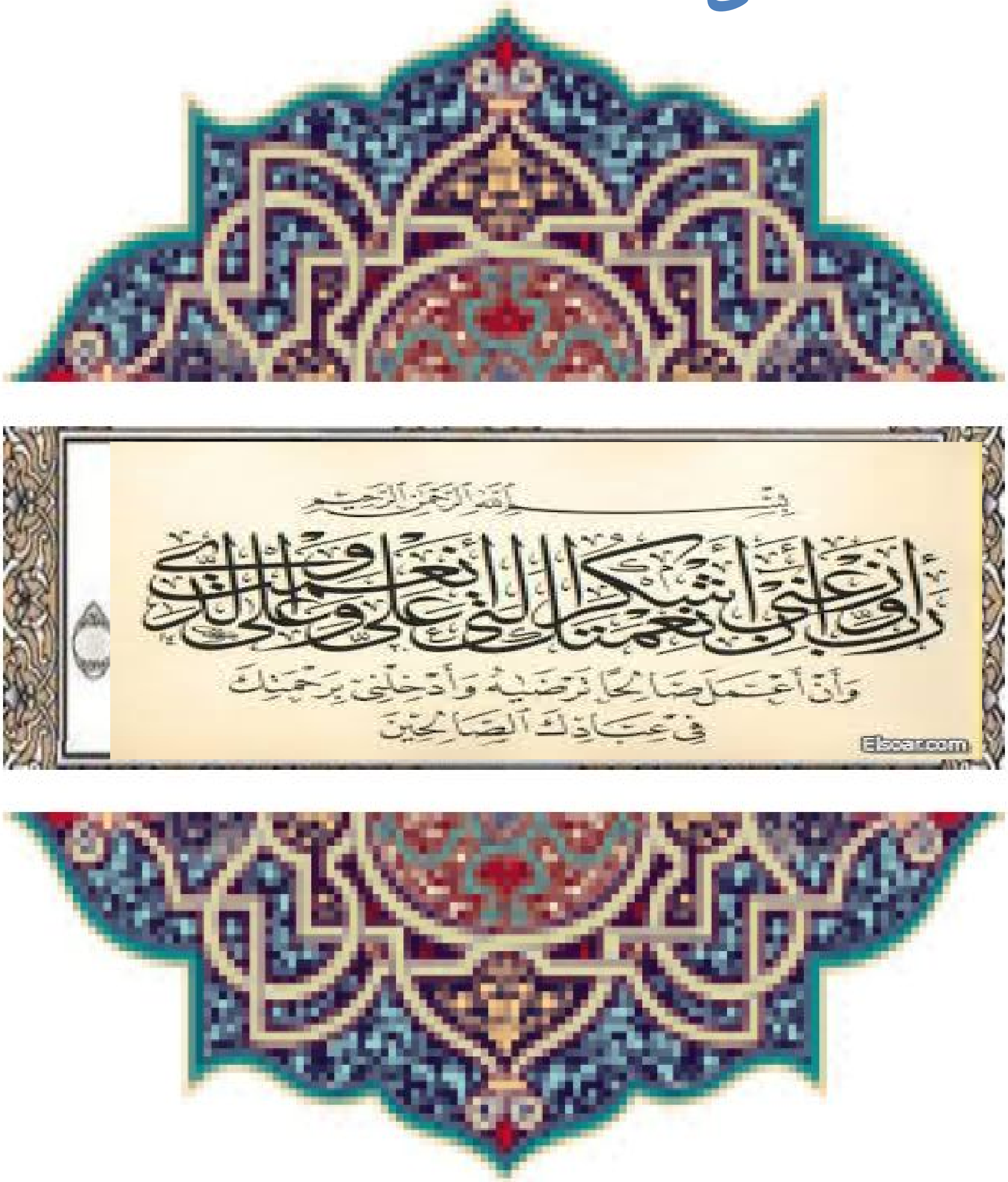

Dedication

الإهداء

إلى القلب الحنون من كانت بجانبنا بكل المراحل التي مضت من تلذذت بالمعاناة وكانت شمعهتحترق لتنير دربنا

....إلى أمهاتنا الحبيبات

وإلى من علمنا أن نقف وكيف نبدأ الألف ميل بخطوة إلى يدنا اليمنى إلى من علمنا الصعود وعيناه تراقبنا

....آبائنا

لمن أمسك بيدينا وعلمنا حرفا ..حرفا ..سنهدي له نجاحنا اليوم إلى من كانوا سندا لنا

إلى من لهم الفضل بإرشادنا إلى طريق العلم والمعرفة

.....إلى أساتذتنا الأفاضل

كم نحن فخورون بكم أصدقائنا وأحبتنا ومن سهروا معنا في مسيرتنا العلمية إلى من مدوا أياديهم البيضاء في ظلام الليل وكانوا عونا لنا

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شكر و عرفان

الشكر و الحمد لله الذي بفضله و توفيقه تم هذا العمل

الشكر الجزيل لمشرفنا الذي لم يبخل علينا بجهد أو وقت أو توجيه

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و الشكر أيضا لكل من وقف بجانبنا و ساندنا لإتمام هذا البحث

و نخص بالشكر قسم هندسة الطيران بجامعة السودان للعلوم و التكنولوجيا متمثلا في

الدكتور صخربابكر

المستخلص

يهدف هذا البحث إلى تحديد و دراسة خصائص الارتفاع و السرعة لإداء محرك تربو شافت مناسب للهيليكوبتر حول استهلاك الوقود و القدرة المتاحة من المحرك عند العمل خارج الحالة التصميمية و عند ظروف طيران غير قياسية, و ذلك خلال طور التصميم الأولي للمحرك.

تم في البدء تعيين محددات التصميم من خلال مواصفات متاحة لمحرك روسي (TV3-117 VMA series (2)). من ثم تمت دراسة الدورة الحرارية بارامتريا, لتعيين خواص (الحرارة و الضغط) الهواء و الغاز عند كل مقاطع المحرك و ذلك عند الحالة التصميمية, وضعت مخططات توضح تغير الخواص على طول المحرك. من ثم تمت دراسة محددات شكل و مواصفات مكونات المحرك الرئيسية, و تعيين قيم الكفاءات. بعدها تم اعتبار جريان الهواء خلال الماكينة و النتائج المتحصل عليها من دراسة المكونات لتحديد أبعاد المحرك الرئيسية و عدد المراحل في التوربينة و الضاغط. تم رسم الشكل النهائي للمحرك باستخدام برنامج أوتوكاد.

في النهاية تم تحليل أداء الدورة الحرارية عند العمل في ارتفاعات و سرعات خارج الحالة التصميمية و في ظروف طيران غير قياسية بتحديد درجات حرارة ($-50 - 35^{o}C$) لكل إرتفاع حتى 3000 متر. تم تحديد خصائص الارتفاع و السرعة لإداء المحرك عند الحالة التصميمية و الغير تصميمية و تمثيلها في مخططات و مناقشتها.

استنتج أن شكل المحرك المتحصل عليه له نفس أبعاد و أوصاف المكونات للمحرك المعطى. أيضا خصائص أداء المحرك تظهر أن تغير استهلاك الوقود و القدرة المتاحة من المحرك يتسم بالنقصان و ذلك بزيادة الارتفاع و الحرارة و الماخ و العكس صحيح.

Abstract

This project is aimed to determine and study the altitude and speed characteristics of the turboshaft engine suitable for helicopter applications, about specific fuel consumption and power available when operated at off-design condition and non-standard flight conditions, and that through a preliminary engine design.

Initially, the design parameters were obtained by an existing Russian engine specifications (TV3-117-VMA series (2)). Then the parametric cycle were studied at on-design condition to specify air and gas properties at all sections of the engine. Graphs were plotted showing the variation of the properties along the engine. Then the flow through the machine and the results from the components study were considered, to determine the major dimensions of the engine, turbine and compressor number of stages. By using the computer program Autocad, the final configuration of the engine were drafted. At the end, the performance cycle were analyzed when operated at off—design condition and non-standard flight conditions by range the temperature from $(-50 - 50\,^{o}C\ \ )$ for every specified altitude to 3000 m. finally the altitude and speed characteristic of the engine performance were determined at design condition and off-design condition, and represented by graphs and discussed.

As a result, the resulting configuration of the engine has the same components dimensions and descriptions of the actual engine . Also the engine performance characteristics shows that the variation in engine specific fuel consumption and power output have a reduction sense when increasing altitude temperature andMach number, and vice versa.

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List of Symbols

Alphabetic Symbols

c	Blade chord
c_{pc}	constant average value of specific heat of air
c_{pt}	constant average value of specific heat of gas
D	Diffusion Factor
E	Energy
g_{fuel}	Fuel to air ratio
H_u	Fuel heat capacity
h	Enthalpy
h_o	Stagnation enthalpy
L_c	Adiabatic work of the compressor
L_{eff}	Effective work of the compressor
$(L_{eff})_{FT}$	Effective work of the free turbine
M	Mach number
$\dot{m}$	Mass flow rate of the air
$\dot{m}_f$	Fuel flow rate
P_{FT}	Power of the free turbine

p	Pressure
P_0	Stagnation pressure
Q	Heat
R	Ideal gas constant
S	Entropy
s	Blade spacing
T	Temperature
T_0	Stagnation temperature
u	Axial velocity
v	Specific volume
W	work
Z	Zweifel Coefficient

Greek letters symbols

η_{out}	Thermal efficiency
σ_{intake}	Intake total pressure recovery
π_c	Compressor total pressure ratio
π_t	Turbine total pressure ratio
π_e	Exhaust pressure ratio
π_s	Stage Pressure Ratio

$\sigma_{c.ch}$	Burner pressure ratio
τ_c	Temperature ratio of the compressor
τ_t	Temperature ratio of the turbine
$(\eta_c)_{ad}$	Compressor adiabatic efficiency
$(\eta_c)_{pol}$	Compressor polytropic
$\eta_{c.ch}$	Combustion efficiency
$(\eta_t)_{ad}$	Turbine adiabatic efficiency
$(\eta_t)_{pol}$	Turbine polytropic efficiency
γ_a	Ratio of specific heat of air
γ_g	Ratio of specific heat of gas
σ	Solidity
Λ_c	Compressor degree of Reaction
Λ_t	Turbine Degree of Reaction
τ_s	Stage Total Temperature Ratio
ω	Angular velocity of the rotor
η_s	Stage Adiabatic Efficiency
ψ	Stage Loading Coefficient
Φ	Stage Flow Coefficient
φ_{cr}	Rotor Loss Coefficient

φ_{cs} Stator Loss Coefficient

Chapter One

Introduction and Literature Review

1.1Preface

Due to the unique operating characteristics of the helicopter, it has been chosen to conduct tasks that were previously not possible with other aircraft or were too time– or work-intensive to accomplish on the ground– at various areas and circumstancesmay involve mountaineer,azalea, iciness and wateriness. The functions which the helicopter is designed for aretransportation, construction, firefighting, search and rescue, and a variety of other jobs that require its special capabilities.

One of the percipient flight conditions of the helicopter is maintaining in nearly motionless flight over a reference point at a constant altitude and on a constant heading (hovering).

The helicopter is intended to flight at low altitudes and speeds where the ambient condition is always affected by the weather conditions and differences according to such circumstances.

1.2Problem Statement

When the helicopter is performing its tasks especially at hovering, such ambient conditions affecting its engine performance (power available and specific fuel consumption)by incorporating the effects of temperature, speed and altitude.The engine power available is directly proportional to the density ratio.Any factor that affects engine performance affects overall vehicle performance.As from the propulsion perspective, these two variables indirectly account for the range, airspeed, payload, and hover capabilities of the overall vehicle.

1.3Proposed Solution

From the design perspective, when designing such turboshaft engine suitable for helicopter applications, altitude and speedcharacteristics of the engine performance−at which the engine is operated− at different temperatures should be considered,that massively affecting the engine performance. This will determine the degree of engine performance affection subjected to such conditions.

1.4Methodology

The altitude and speed characteristic of theengine performance will be obtained within a preliminary design which it's calculations can be used as a cyclic performance analysisduring service term of the engine. As a design tool, the design input parameters is obtained using an existing engine data.

The first phase of this project, is the parametric cycle analysis (on-design condition), which is determining the properties(pressure and temperature) of the air and the gasat all sections of the engine (inlet, compressor, combustion chamber, turbine, exhaust). Also its maintaining the major dimensions of the engine, compressor and turbine number of stages, power available and specific fuel consumption is.Thus, incorporating these results a preliminary turboshaft engine design is produced at on-design condition (zero altitude and Mach number).

The second phase, is the performance cycle study of the engine (off-design condition). It were analyzed analytically and presented via (ME) program at various altitudes non-standard conditions, within temperature range (-50−35)C□ -for every specified altitude-and Mach number (M=0,0.15,and 0.3). The third phases,presenting altitude and speedcharacteristics of the engine performance graphically by plotting both parameters of the engine performance (specific fuel consumption and power available) against the various altitudes non-standard conditions and the specified Mach number's. It should be noted that the speed characteristics were determined at (H=100 m) where the hover condition is obviously affected by the ambient conditions.

1.5 Objectives

The main aims of this research is effort to:

- Through a preliminary design, studyingaltitude and speed characteristic of the engine performance (specific fuel consumption and power available) when its operated at flight conditions out of the design conditions
- Parametric cycle analysis to determine air and gas properties at all sections of the engine
- Performance cycle analysis to determine the main dimensions of the engine, compressor and turbine number of stages, specific fuel consumption and power available
- Show the final engine configuration and dimensions by sketch and illustrating the flow properties at all sections in the sketch
- Determine the engine performance altitude characteristic at design condition (M=0) and standard altitude conditions
- Determine the engine performance altitude characteristic at off design condition (M=0.3) at non-standard conditions
- Determine the engine performance speed characteristic at constant altitude and at standard & non-standard conditions

1.6 Research outline

Chapter One: Introduction to the main topic and the motivation of this study and the objectives of it. Fundamentals for the topic with literature review for existing studies on the same topic using different methodologies for the same purpose.

Chapter Two: Preliminary design methodology of the turboshaft. And introducing for engine performance characteristics.

Chapter Three: Calculations applied for preliminary engine design and performance characteristics.

Chapter Four: Plotting the results for performance characteristics and discussing them. Also representing the results from the preliminary design in diagrams and drafting the final engine configuration.

Chapter Five:Conclusion and recommendations for future studies.

1.7Literature review

1.7.1 Fundamental Propulsion System Concepts

Before exploring the specific design and analysis techniques used for turboshaft engines, it is important to first review some of the basic concepts and assumptions of thermodynamics.

1/ Work and heat:

- **Heat (Q)**: is defined as the form of energy that is transferred across the boundary of a system at a given temperature to another system at a lower temperature by virtue of the temperature difference between the two systems.[1]

- **Work (W)**: is similar to heat in that it only exists as an interactive quantity and can be defined such that work is done by a system if the sole effect on the surroundings (everything external to the system) could be the raising of a weight.[1]

2/Energy, enthalpy, and entropy:

- **Energy (E):** is simply defined as the measure of a system's potential to perform work. The forms of energy most applicable to thermodynamics problems are kinetic energy (due to motion), potential energy (due to position), and internal energy (sum of kinetic and potential energy at the molecular level).
- **Enthalpy (h):** is an extensive property used to describe the sum of the internal energy of a system and the energy of the work done by the system on its surroundings. The following equation best describes this relationship:

$$h = u + pv \qquad (1.1)$$

- **Entropy (S):** is another extensive property of matter that measures the degree of randomization or disorder.The change in entropy is used to determine the efficiency of a process in terms of its proximity to the limits of what is "ideally" possible.

Along with these definitions, there are several fundamental assumptions that help to describe and simplify thermodynamic processes.

3/ An adiabatic process: Is one in which there is no transfer of heat.

4/ An isentropic process: Is an adiabatic process where there is no change in entropy.

In terms of fluid mechanics, the flow properties are assumed to be steady and one-dimensional.

5/Steady flow: Means that the fluid properties such as velocity and density at any point in a space do not vary with time. In control volume scenarios, this assumption greatly simplifies the problem by eliminating the need to consider the behavior of the control volume contents – only the inputs and outputs affect the thermodynamic analysis.[3]

6/ One-dimensional flow: Also known as uniform flow, means that the fluid conditions are assumed to vary only in the direction of the streamline.[3]Although this assumption fails to address the multi-dimensional flow properties that exist near a wall, historical precedence has shown that it still provides a meaningful approximation in the study of fluid thermodynamics.

7/ First law of Thermodynamics: The concept of conservation of energy is defined by the 1st Law of Thermodynamics for a control volume which can be written as follows:

$$\frac{dE}{dt} = \frac{dQ}{dt} + \frac{dW}{dt} \qquad (1.2)$$

8/ Secondlaw of Thermodynamics The 2nd Law of Thermodynamics states that it is impossible to construct a heat engine that operates in a cycle, receives a given amount of heat from a high-temperature body, and does an equal amount of work.[3]

$$dS \geq \frac{\delta Q}{T} \qquad (1.3)$$

9/ Ideal Gas Properties: The equation of state for a perfect gas as follows: $pv = RT$, This equation of state establishes the definition of a pure substance as one that has only two independent static properties.

10/Brayton Cycle

The Brayton cycle as shown in figure (1-1) is the thermodynamic model used to describe an ideal gas turbine power cycle. The four key processes of the ideal Brayton cycle are described below:

- Isentropic compression (2 – 3)
- Constant-pressure heat addition (3 – 4)
- Isentropic expansion (4 – 5)
- Constant-pressure heat rejection (5 – 1)

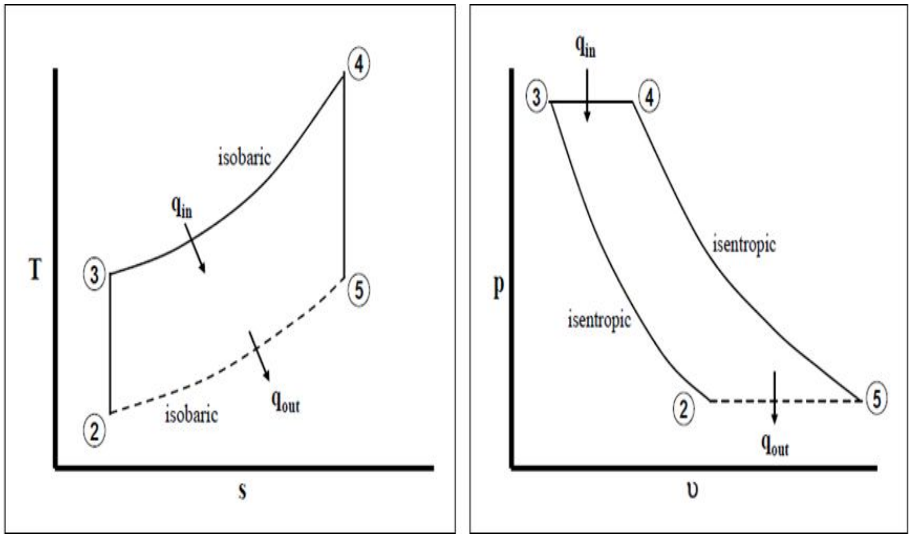

Figure 1-1: Ideal Brayton Cycle Diagrams (Open-Cycle)

The ideal compressor stage, from 2 to 3, is where mechanical work is performed on the fluid causing an isentropic rise in both enthalpy (or temperature) and pressure. During the ideal combustion stage, from 3 to 4, heat is added to the fluid by burning a mixture of fuel and air at a constant pressure – greatly increasing its enthalpy.In the ideal turbine stage, from 4 to 5, work is mechanically extracted from the fluid through isentropic expansion. The common shaft connection between the turbine and the compressor sections is what allows the work extracted by the turbine to be translated into the driving force for the compressor.

11/Thermal Efficiency and Work Output

The thermal efficiency term is used to define the ratio of gas turbine work output to the energy input from burning fuel, as follows:[2]

$$\eta_{out} = \frac{netW_{out}}{Q_{in}} = \frac{net\,W_{out}}{m_f\,\Delta h} \qquad (1.4)$$

12/Preliminary designprocedureof the turboshaft engine

With the fundamental concepts of thermodynamics and gas turbine engines established, it is now time to focus on the preliminary design and analysis of the turboshaft engine as it relates to rotorcraft applications. For designing a turboshaft engine there must be an interrelationships between thermodynamic, aerodynamic, mechanical and control system design and a need for feedback between the various specialist to obtain the optimum design. There are many turboshaft engine design methodologies. Each one of them has it's own design loop that identify the design parameters through analysis of a design requirements within mission analysis, operated envelope analysis and propulsion system requirements.

The major design step for the preliminary design is to carry out thermo dynamic design point studies as for Georgia Tech Generic Helicopter (GTGH) preliminary design loop shown in figure (1-2). These are detailed calculations taking into account all important factors such as expected components efficiencies, air-bleeds, variable fluid properties and pressure losses, and would be carried out over a range of pressure ratio and turbine inlet temperature. A value for specific output (i.e power per unit mass of air) and specific fuel consumption will be determined for various values of the cycle parameters listed above.

After the design input parameters been determined the parametric cycle analysis and performance cycle analysis will be accomplished to obtain the engine performance at off-design conditions.

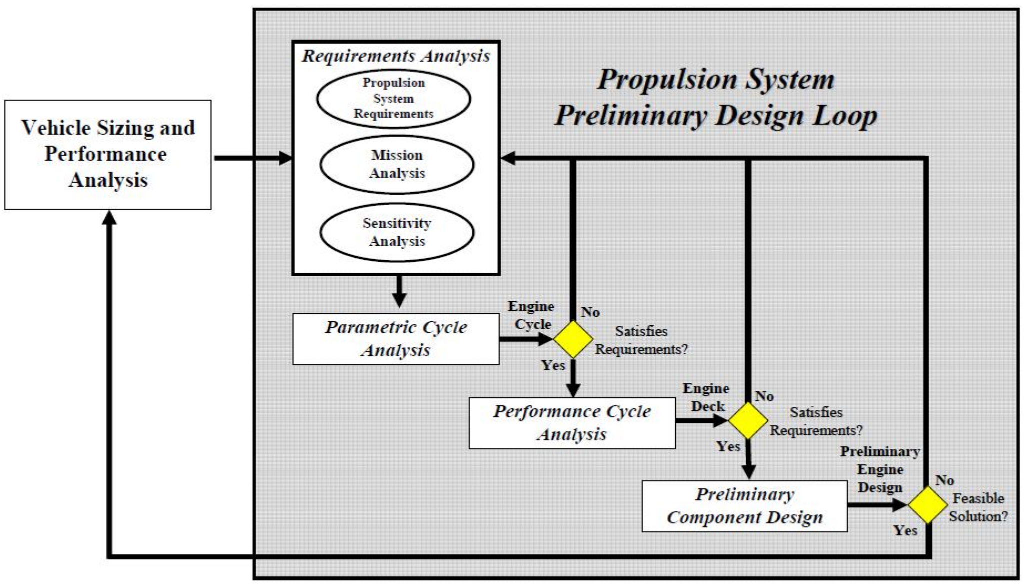

Figure 1-2: Integrated Propulsion System Design Methodology

1.7.2The atmosphere

The atmosphere is the medium in which helicopters fly but it is also one of the fuels for the engine and the occupants breathe it. It is a highly variable medium that is constantly being forced out of equilibrium by heat from the sun and in which the pressure, temperature, and humidity can vary with height and with time and in which winds blow in complex time- and height-variant patterns. The effect of atmospheric conditions on flight is so significant that no pilot can obtain qualifications without demonstrating a working knowledge of these effects.

The gas law states that the product of pressure and volume is proportional to temperature. Reducing the volume means that external work has to be done to oppose the pressure. This work increases the temperature of the gas. The Diesel engine obtains ignition in this way. Conversely if the volume is increased, work is done by the gas and the temperature must fall. This is why carburetors are prone to icing on part throttle because the air expands on entering the manifold. Air conditioners work in the same way. If the volume is fixed, as temperature rises, the velocity of the molecules increases and so the impact at each collision with the walls of any container is greater and the pressure rises. Alternatively the same pressure can be exerted in a given volume with
a smaller mass of gas. Thus in the atmosphere where pressure increases can be released by free movement, the result of an increase in air temperature is that the density goes down. Density is also affected by humidity. Water molecules are heavier than those of atmospheric gases and increase the pressure due to molecular collisions. Thus in the
presence of water vapour a given pressure can be sustained with a smaller mass of air and the density goes down.

1.7.2.1International Standard Atmosphere

In order for meaningful comparisons to be made between various test results, it is important to eliminate variations due to atmospheric conditions. The International Standard Atmosphere (ISA) is a defined set of fixed conditions,

somewhere within the spread of conditions found in practice. When a test is made, the actual atmospheric conditions are measured. Using the laws of physics, it is possible to calculate the effect
of every difference between the actual conditions and ISA. If all results are corrected in this way, they can be presented with respect to ISA and as a result can immediately be compared with any other results obtained in the same way. Similarly, if the performance of a machine is defined in the flight manual with respect to ISA, it is possible to correct for the actual conditions and predict the real performance that can be expected.

In the ISA, pressure and temperature at mean sea level (MSL) are defined, along with standardized rates at which these change with height. Relative humidity (RH) is also defined to be zero. ISA MSL pressure is 101.3kPa. Temperature is 15◦C and the density is 1.225 kg/m3. The ISA lapse rate defines temperature as falling at 1.98◦C per 1000 feet (which is a mongrel unit being part metric and part imperial). Although
the height of the tropopause is a function of latitude because the earth is rotating, ISA defines the tropopause as 36 000 feet and above this the air temperature is−56.5◦C. For many purposes the approximation of −2◦C per 1000 feet can be used as the lapse rate. Given the above, the pressure and density of the ISA can be calculated for any height above sea level. The density is important because it directly affects the power that can be produced by the engine(s) and the thrust produced by the rotors.