ANALYZE OF THE NEW AIRCRAFT ENGINE DEVELOPMENTS OF ADVENT, OPEN ROTOR, GEARED FAN AND LEAP GAS TURBINE ENGINES. CONSIDER THE ENVIRONMENTAL, COMMERCIAL AND TECHNOLOGICAL ASPECTS

Acknowledgement

It provides me greatest satisfaction to make the final submission of the research that focuses on the research title **"Analysis of the new aircraft engine developments of ADVENT, Open Rotor, Geared Fan and LEAP Gas Turbine Engines along with Consideration of the environmental, commercial and technological aspects"**. I am grateful to various fellow members behind the successful completion of this research.

I would like to express thanks to number of people who have guided me in preparing this research. I would like to thank my higher authority, since without their guidance my project work would not have been achievable. I would also like to thank my peer group members. I would also like to show my appreciation towards the respondents of the surveys as well as the interviews, whose co-operation has helped me to incorporate data collection effectively and efficiently.

Thank you,

Abstract

According to the current scenario of the airline industry, competitiveness has increased up to a new level after globalization of the industry. In relation to the rapid advancement of the aircraft engineering and science, several advanced technologies are being included in aircraft manufacturing. Lots of research works are carrying on to increase the efficiency of the aircraft engines as it is known that rate of fuel consumption of public carrying and cargo aircrafts are pretty large for commercial usage. In this research work, development of the advanced aircraft engines is discussed in details by considering environmental, commercial and technical aspects.

Due to a lot of research and development of aircraft engines of aircrafts are used for commercial purposes like CFM engines, GE engines, and other shaft engines. During a production of this engine, environmental impact regarding the exhaust of the combustion is also considered and possible sophisticated accessories are implemented according to the requirement to reduce the pollution.

Environmental degradation and depletion of the oil and other fuels are becoming a devastating issue. Due to this reason, environmental consideration and high fuel consumption rate are of deep concern in the aircraft industry. Due to lower engine efficiency, sometimes the flight fare becomes unaffordable for the public. This is considered as one of the primary concerned issue of this dissertation. In the literature review section of this dissertation, detailed explanation of ADVENT engine, gas turbine aircraft engine, open rotor engine, Leap engine, geared turbofan are provided in terms of the efficiency, specifications and other design aspects. In the design part of these advanced engines, development of the constructional components is also included in the literature review section.

Methodology chapter of this research dissertation has provided specification regarding different methodological layers. Positivism philosophy, deductive research approach and the descriptive research design has been followed in this dissertation in order to obtain the research objectives in the most effective way. Data collection is done from only secondary data resources like journals, online articles, ebooks, websites, and specification charts. In the analysis section, both quantitative and qualitative data are critically analysed. Thematic technique has been obtained for analyzing the collected data in this research work. The quantitative analysis is done with

respect to the specification of the advanced aircraft engine. The specification parameters are chosen in terms of dimension of the fan blade, acquired floor space, expected efficiency of the engine, capacity of the engines in generating takeoff thrust and others. Comparative study regarding three different types of Leap engines is also included in the analysis section. In case of qualitative analysis, material requirements for manufacturing the engine components are analysed in brief. Selection of the most suitable alloy material is important in case of the production of the fan, engine casing and other components.

At the end of the dissertation, conclusion section produces the linkage of different parts of the dissertation is explained in terms of the research objective and research questions. Possible recommendations are provided for improvement of the experiments. Obstacles faced during conduction of this research work and the future scope is also provided in the conclusion chapter.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Introduction

Competitiveness in the market of aircraft manufacturing industry has increased remarkably in last few years. In relation to the rapid advancement of the aircraft engineering and science, several advanced technologies are being included in aircraft manufacturing. Lots of research works are carrying on to increase the efficiency of the aircraft engines as it is known that rate of fuel consumption of public carrying and cargo aircrafts are pretty large for commercial usage. Fuel consumption of fighter flights is even greater. According to Angi and Huminic (2015), engines and propelling technologies can be divided into various subparts for separate investigation regarding the improvement of efficiencies. In this dissertation, aircraft engine design is to be discussed in advanced form including the separate discussion regarding the gas turbine engine design, LEAP and open rotors implementation in aircraft engine design.

1.2 Background of the research

This research paper is concentrated on the development of advanced aircraft engine. Realization of the future prediction regarding the inclusion of most advanced technologies in aircraft engine design to increase the efficiency of the engine up to a certain desirable level are also provided in this dissertation. According to the current scenario of aircraft manufacturing industry, maximum commercial aircrafts are found to be powered by the gas turbine engines. According to Kennedy and Martins (2014), a gradual increase of the gas turbine engine efficiencies helps in the reducing the fuel consumption. The inclusion of the open type rotor, ADVENT, and the LEAP into the aircraft manufacturing industry is also provided with proper description.

In this dissertation, several systematic research regarding different components of gas turbine powered engines, LEAP, open rotors and geared fans are found for preparing a specific platform of knowledge to meet the research demand according to the research aim and objectives, which are determined at the next sections of this chapter.

The increase of the engine efficiencies directly reduces the rate of fuel consumption and flying cost can be reduced to a certain level. According to Salehnasab *et al.* (2016), as per the selection of the aircraft manufacturing design and selection of the engine helps in determining the rate of fuel consumption according to the requirement. In case of fighter planes, efficiencies re not of much concern, the main concerned thing is the capacity and sophistication of the aircraft and engine design.

1.3 Rationale of the Research

In the recent time, research work regarding aircraft manufacturing industry has advanced a lot including higher-level sophistication in the engine. Safety levels of the body of the aircraft are also increased gradually along with the development of improved and advanced engines. According to Lu *et al.* (2014), the main issue of the aircraft engine is to reduce the rate of fuel consumption. Due to a lot of research and development of aircraft engines of aircrafts are used for commercial purposes like CFM engines, GE engines, and other shaft engines. During a production of this engine, environmental impact regarding the exhaust of the combustion is also considered and possible sophisticated accessories are implemented according to the requirement to reduce the pollution.

Environmental degradation and depletion of the oil and other fuels are becoming a devastating issue. Due to this reason, environmental consideration and high fuel consumption rate are of deep concern in the aircraft industry. Due to lower engine efficiency, sometimes the flight fare becomes unaffordable for the public.

Due to lower efficiencies, the airline companies find many difficulties to manage the loss. According to Kuz'michev *et al.* (2014), airline and aircraft manufacturing companies are obliged to act according to the environment conservation act to implement advanced technologies to reduce the emission from engines.

In this dissertation, a detailed discussion regarding the gas turbine engines, geared fan, implementation of the open rotor, ADVENT system and LEAP in accordance with the science of aircraft engineering. Some specific recommendations are to be provided to increase the efficiencies of the aircraft engines so that the flight fares drop down to more comfortable level for general people. Additional use of the accessories in preventing air pollution is to be discussed in this dissertation considering the environmental degradation.

1.4 Research aim

This section of this dissertation would determine the aim of this research work regarding the aircraft engine. Research aim can be stated as to obtain a critical analysis regarding the development of advanced aircraft engine by considering some commercial, environmental and technical aspects.

1.5 Research objectives

Research objectives can be determined in the following way.

- To analyze and explain development of new aircraft engine of ADVENT systems, open rotor, geared fan, LEAP and gas turbine
- To consider environmental , technical and commercial aspects in the aircraft engine design
- To outline possible recommendations for improvement of the engine efficiencies and reducing engine emissions

1.6 Research questions

Research questions can be formed as follows.

1. How can an aircraft engine of ADVENT, LEAP, gas turbine, geared fan and open rotor be developed?
2. How the environmental, technical and commercial aspects be be considered in aircraft engine design?
3. What are the possible recommendations to improve the engine efficiency and to reduce the rate of the emissions into the environment?

1.7 Significance of this study

Depletion of fuel and pollution can be considered as two of the most concerned topic in recent aircraft engineering scenario. In this dissertation, different technologies are to be discussed in terms of aircraft engine design to recommend a possible solution of the predetermined research questions. This research dissertation is expected to provide a detailed background knowledge regarding technical aspects of aircraft gas turbine engine.

1.8 Structure of the dissertation

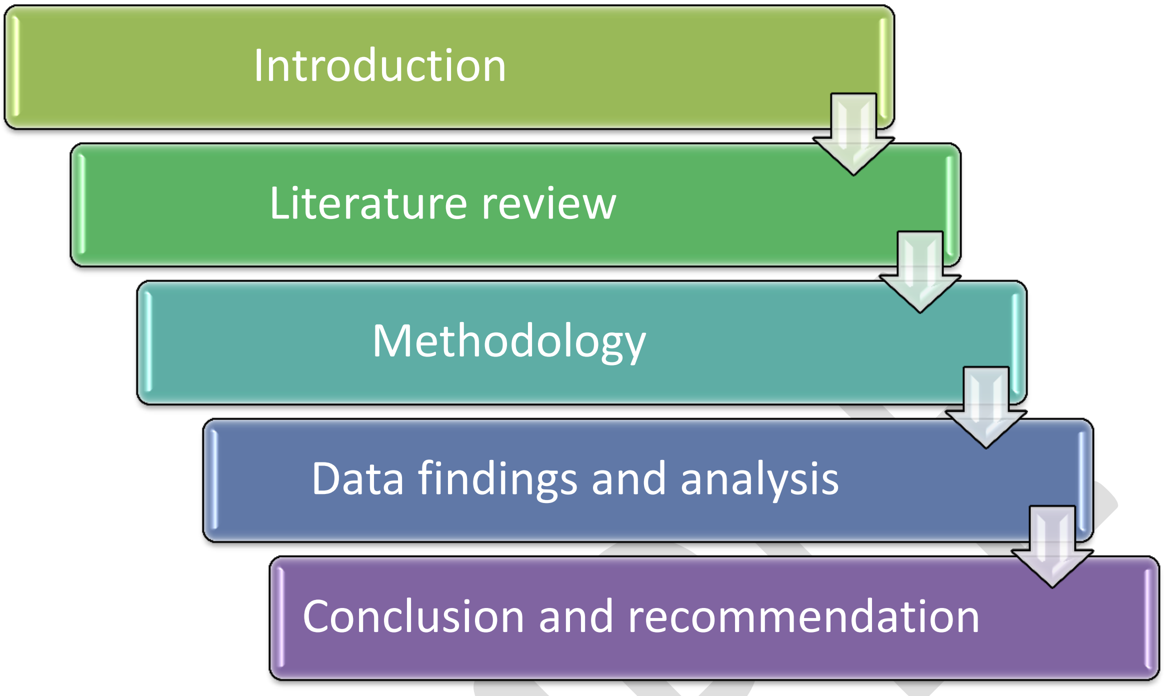

Figure 1.8: Structure of the dissertation

(Source: Self created)

1.9 Summary

The first chapter of the dissertation provides a platform for background knowledge regarding the research topic selected before the beginning of this dissertation. Research rationale is prepared to know the issue regarding the research subject. Aims and objectives are determined in this chapter to obtain a specific direction of the research work according to the capability of the researchers. In the next chapter, sufficient amount data collection is done to provide a platform to produce an effective answer to the research questions.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter of the dissertation can be considered as the platform of the productive research work. Adequate background study regarding the research topic is done in this section. Some specific relevant selected theories, models and concepts are linked with the background study. As per the research requirements, a conceptual framework is to be prepared to link with all the research variables within it. There are several modern research works on avionics and aircraft engine design. Those research papers are analyzed and evaluated for obtaining a satisfactory answer to the research question. A gap between previous research works and the current research findings are evaluated in this chapter. A gap in the literature is analyzed to make a bridge between the previous research findings and the current research requirements.

2.2 Conceptual Framework

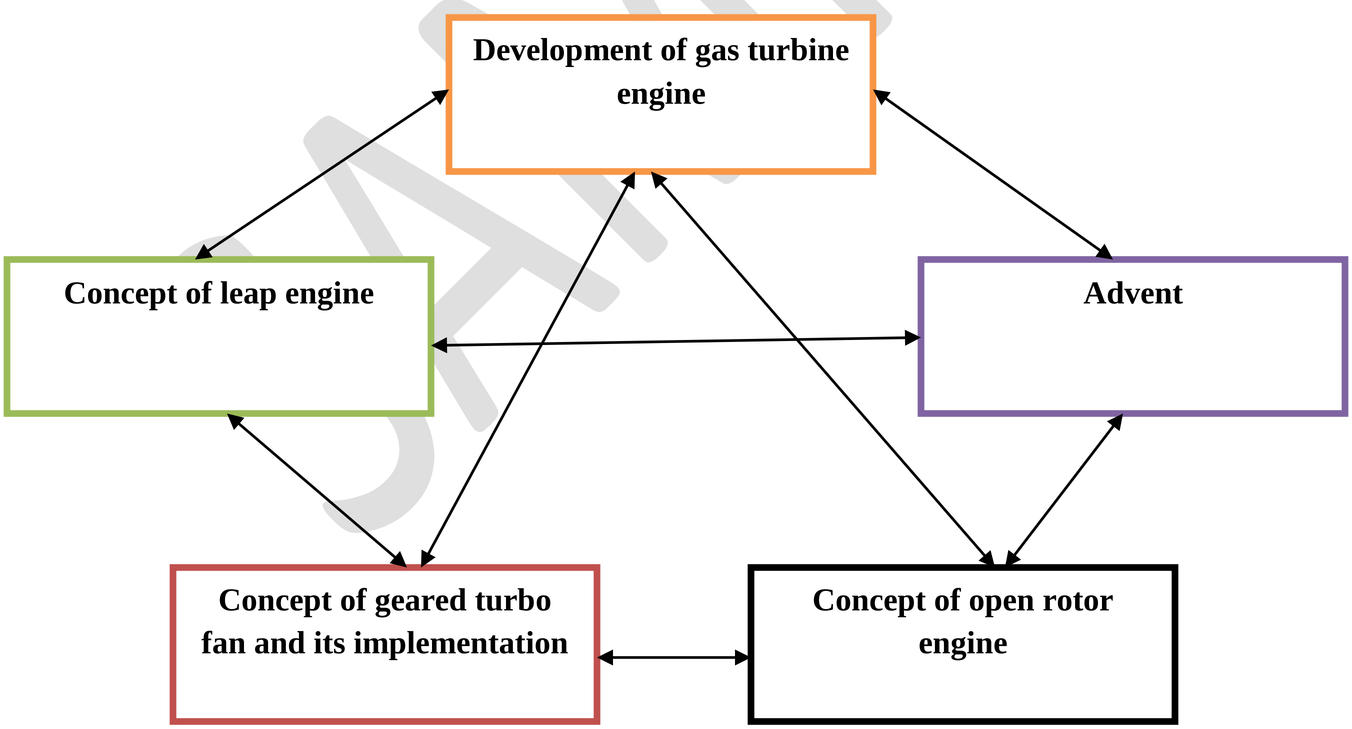

Figure 2.2: Conceptual framework

(Source: Self created)

2.3 Gap in the literature

According to the current scenario of the aircraft designing and manufacturing of the engine, competitiveness of the market has been increased significantly. Hence the increase of the efficiency of the aircraft engine with consideration of the environmental factor has become the primary concern for the engineers in case of designing an aircraft engine. It enables the chances of commercialization of the engines for sake of common passengers. Gap in the literature has been found regarding the application criteria of several advanced aircraft engines, because these engines are still under research and development. However, the explanation regarding possible maintenance cost, implementation cost of these engines cannot be obtained due to lack of commercialization. Some specific requirements regarding the possible effective tolerance of assembly design and design of engine construction are still unknown because these kinds of data are not published publicly due to some technical and research issue. Approximate specification and the fuel; efficiencies are obtained from the data achieved from small prototype testing by some famous mechanical aircraft engineering institute. Yet several research works are yet to publish regarding the detailed description of modification made for increasing the efficiency of aircraft engines.

2.4 Development of gas turbine engine

According to the current scenario, it has been found that majority of the commercial aircrafts are powered by the gas turbine engines. These engines can be of either turbo fan or the turboprop. In the discussion of the reduction of carbon emission from the aircraft engines, improvement of the gas turbine engine is concerned. The current state of the aircraft engine desk will be provided in this section to provide a brief idea regarding the scopes and possibilities of improvement.

Engine refers to a machine that absorbs fuel energy to produce mechanical energy in terms of rotation of the shaft of the propeller. Aircraft flying mechanism is dependent on the propelling mechanism. According to Rao *et al.* (2014), engines have become highly integrated with the form of turbofan or turboprop. Air is drawn through the propeller blade to produce the required amount of background thrust for the aircraft. 80 % to 90 % exhaust drained out to the atmosphere through the nozzle of the fan. The entire fluid flow can be analyzed in form of steady flow energy equation. In this equation kinetic energy and potential energy are calculated according to the conservation of the energy and mass. According to Chan *et al.* (2014), remaining fan air is used to pressurize the compressor. Use of this exhaust air can be stated as follows.

1. Colling of the combustion engine
2. Preparation of air fuel mixture

Efficiency: Combustion of the fuel produces exhaust with high pressure, which in turns rotates the turbine of the rotor by producing mechanical rotary energy. Additional thrust is produced when the exhaust gas passes through the turbine. In case of gas turbine engines, the metrics of primary engineering can be discussed in terms of efficiency, weight, drag force, reliability and other mechanical characteristics. According to Tsoutsanis *et al.* (2014), overall efficiency of this kind of engine can be stated as the efficiency of conversion between input power generated from fuel combustion, and the propulsive power. In another it can be stated as the product of thermodynamic efficiency of the process converting power of fuel flow to the shaft rotation power and the propulsive efficiency.

Overall efficiency = thermodynamic efficiency * propulsive efficiency

The most effective commercial gas turbine engine has found to produce a takeoff thrust up to 20000 lb or above. According to Pourbabaee *et al.* (2016), this kind of commercial turbine engines is used in case of cruise with a mechanical dynamic efficiency of more than 54 % and the propulsive efficiency of 70 % and these values are multiplied by 40 % to represent the overall efficiency of a gas turbine engine. According to Zhu *et al.* (2016), design efficiency and the weight of the engine are influenced by the manufacturing cost of these engines. At a constant level of available technology, it can be profitable to trade gas turbine engines for greater efficiency and lower maintenance cost. In case of long range aircrafts, engine specification is selected based on the optimization of the efficiency, dry weight and the manufacturing cost.

Propulsive energy: Propulsive efficiency of the gas turbine engine can be defined as the propulsive power of the power delivered to the propeller of the aircraft engine divided by the input of the shaft power. As per Murugan *et al.* (2015), in case of turbofan aircraft, propulsive efficiency is found to be 70 % to 80 %. Turboprops aircrafts are found to be more efficient in terms of propulsive efficiency.

Type of gas turbine engine: Based on the design of producing shaft rotational power, gas turbine engine can be widely categorized into four parts. These are

1. Turbojet
2. Turbofan
3. Turboprop
4. Afterburning turbojet.

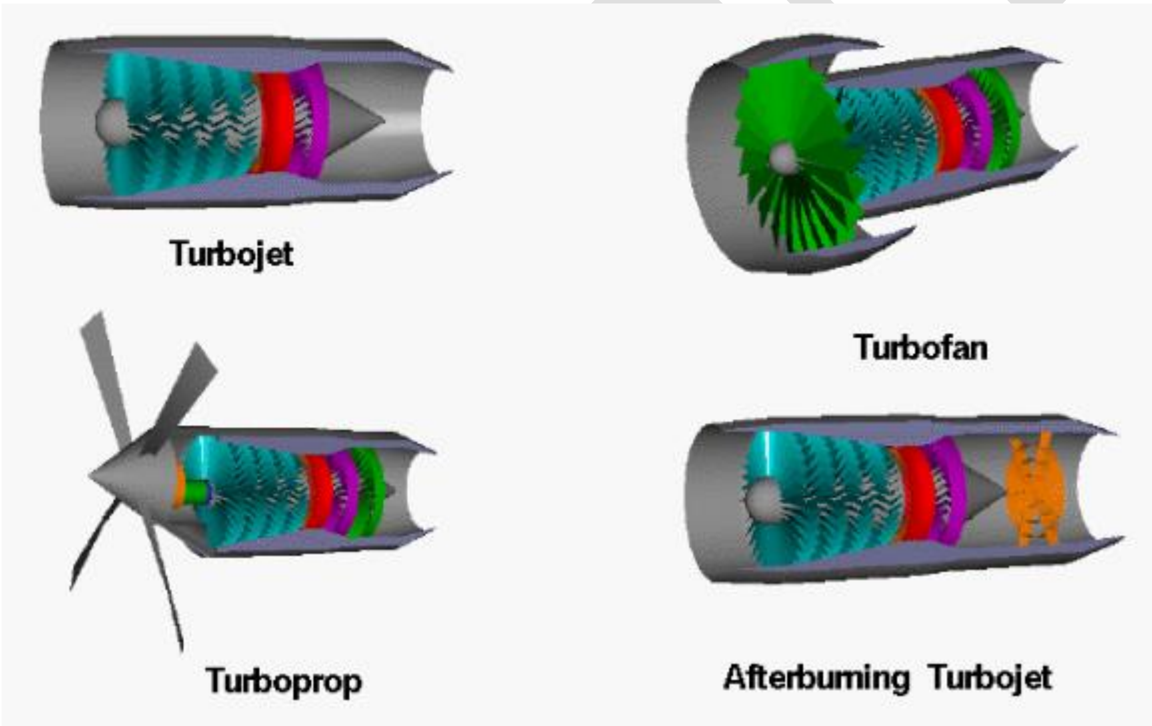

Figure 2.3.1: Types of Gas turbine engine

(Source: Murugan *et al.*, 2015)

According to the given computer aided drawing of the schematic diagram of four different types of a gas turbine engine, it can be said that there are many common parts in each of these types. Red marked portions represents the combustion chamber portion of the engine. Cyan colored portion represents the compressor.

Afterburning turbojet: In case of overcoming the requirement of sharp increase in the drag force to produce aircraft velocity near the velocity of the sound (this velocity is called the sonic velocity), afterburning turbojet is used.

Turbofan engine: Turbofan is a most advanced gas turbine engine, where two spool operations can be done with ease due to some rotating and stationary shaft arrangement. These engines are used in commercial flights for its higher efficiency (Asgari *et al.,* 2016).

Turboprop engine: Sometimes turboprop engines are called turboshaft engine. These kinds of engines are generally used in helicopters and private aircrafts with smaller size and weight.

Turbojet engine: This kind of engines is used in case of the jet engine. Velocity of the flights containing this engine is calculated in terms of Mac number.

Design of gas turbine engine

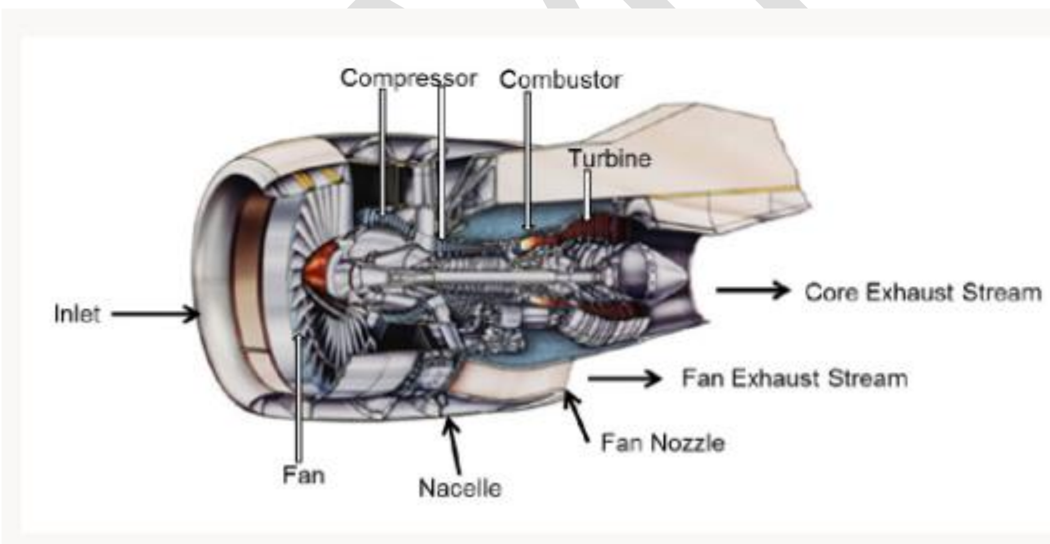

Figure 2.3.2: Gas turbine engine

(Source: Temme *et al.,* 2014)

There are two primary parts of the gas turbine engine. In the front part of the inlet zone of the propeller, inlet air is brought into the engine by means of rotating fan blade mounted on a rotating shaft. This dragged air enters into the compressor zone and then it reaches the combustion chamber. Air fuel mixing is done in the combustion chamber. According to Temme *et al.* (2014), after combustion, unburnt fuel is collected from the exhaust upto a certain percentage of 20 %. Remaining 80 % of the exhaust air passes through the end nozzle portion of the engine. Exhaust is passed through the exhaust fan blade and then it is called as the core exhaust stream, which helps in creating a backward thrust to the aircraft in the forward direction.

Working of the thrust force: before the discussion of the working, it is to be ensured that working fluid of the gas turbine engine is the surrounding air. Thrust force provides the sufficient drag force to move the entire aircraft through the air. According to Wright *et al.* (2015), the propulsion system of the aircraft generates thrust force according to the required amount to move the aircraft. Newton's third law of motion is applied in this operation. Working fluid is accelerated by the nozzle and fan arrangement of the propulsive section within the gas turbine engine. According to Satish *et al.* (2014), general deviation equation of thrust reflects the amount of generated thrust that depends upon the mass flow of the working fluid through the fan nozzle. ***[Referred to appendix 2]***

Improvement of turbofan efficiency:

Several numbers of research works are going with an objective of improving the thermodynamic efficiency of the aircraft gas turbine engine. Improvement of the thermodynamic efficiency would be helpful in reducing the fuel burn. New engine designs are needed to be generated for improvement. In the increase of the thermodynamic efficiency mechanical limitations are not very much clear to the engineers. Improvement of the efficiency can be done in two primary ways.

1. Increase of compressor exit mass flow
2. Increasing the turbine inlet temperature

Loss of structural aerodynamic weight of the engine might be helpful in increasing the overall efficiency of the gas turbine engine. According to the current scenario of large aircrafts, compressor temperature is limited by the turbine temperature due to some technical limitations. These limitations can be stated in terms of corrosion of the turbine blade, mechanical resistance of the blade material, thermal and mechanical characteristics of the blade materials

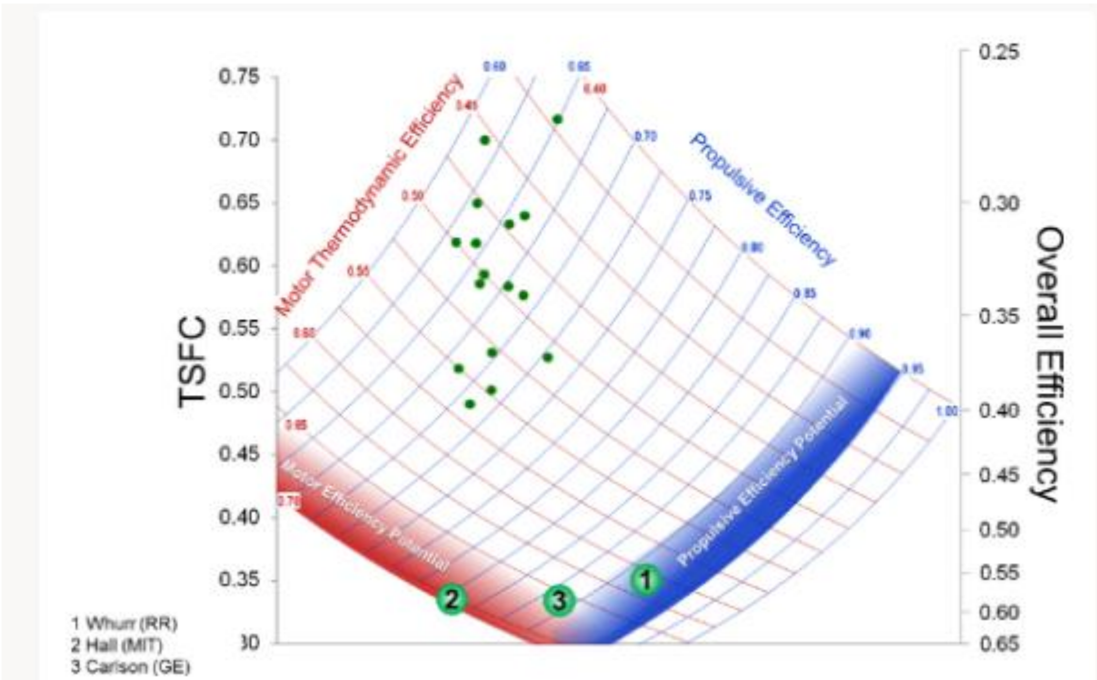

Figure 2.3.3: Efficiency of Gas turbine engine

(Source: Gazzani *et al.*, 2014)

Improvement of propulsive efficiency: Aircraft engines are dependent on the propulsive effects of the fan propellers of the engine irrespective of the source of shaft power. This thrust force generated from the shaft power. According to Gazzani *et al.* (2014), turbofan engines are used in most of the commercial aircrafts with high efficiency. In case of turbofan propulsion, path of the propulsion stream can be stated as inlet> fan> fan duct> fan exhaust nozzle. Improvement of the propulsive efficiency can be done in the following ways.

1. Reduction of the fan pressure ratio
2. Decrease of fan exhaust velocity

Figure 2.3.4: Stream line path
(Source: Self created)

As per the concept of the propulsive efficiency, pressure loss in the internal streamline helps in terms of increase in the fan factor to provide additional energy to flow. Drag lost in inlet and outlet duct walls occurs due to imperfect nozzle expansion of the exhaust air.

2.5 Advent

In order to increase the working efficiency and engine performance in aircraft aviation system, different advanced engine development programs are carried out by aircraft engineers. Among those, US air force has developed a program regarding ADaptive Versatile ENgine Technology (ADVENT) for developing the characteristics of the aircraft engine by means of advanced technologies and scientific inventions. As opined by Kennedy and Martins (2014), the primary objective of this engine development program can be stated as implementation of variable cycle engine (VCE) with higher efficiency in the system of military aircraft of 89 kn thrust class. The amount of thrust generated is labeled in terms of take off thrust.

Aim: The aim of this engine development program can be coined in terms of developing an engine with higher efficiency and which is to be optimizing between separate design criteria. In case of traditional engine design, single point criteria are met for preparing efficient engine. On those occasions, separate engines were used to serve the required criteria regarding the speed or economy. In case of fighter aircrafts, high speed engines are used, where fuel economy is not taken under consideration. According to Wiese *et al.* (2015), in case of commercial engines, speed is not considered as the primary requirement and hence high efficiency engines are used. However, in ADVENT development program, both of these criteria are taken into consideration in order to obtain an optimization for the requirement. The design developed in this program is expected to serve both the purpose regarding efficiency and speed. Average rate of fuel consumption is expected to be reduced by 25 %. It would also help in reduction of the temperature of the cooling air, which is produced by the engine itself (Edelson *et al.*, 2015).

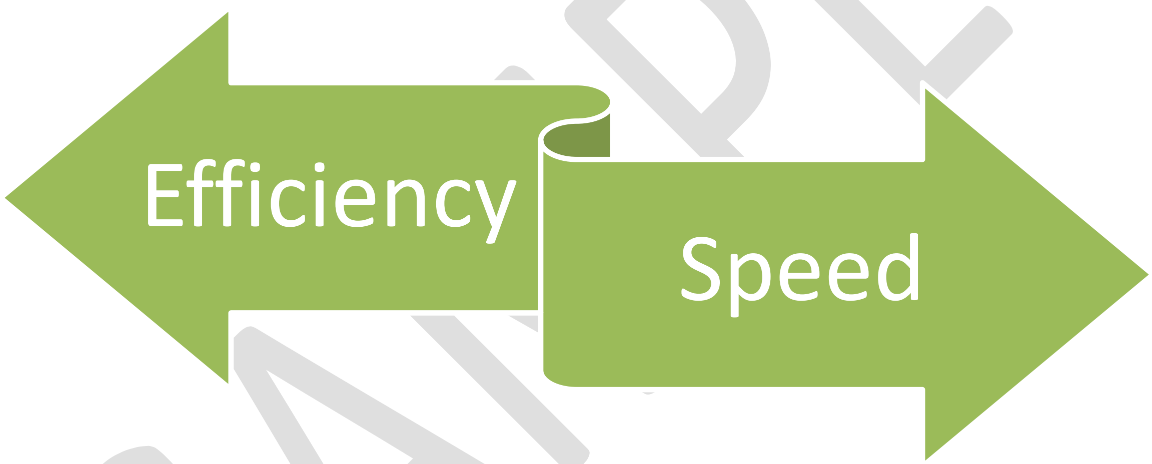

Figure 2.4.1: Criteria optimization for ADVENT

(Source: Self created)

Evolution: ADVENT program can be considered as one of the aircraft project associated with aircraft engine design pursued under the department of US AIR Force, named Versatile Affordable Advanced Turbine Engines (VAATE). According to Gruber *et al.* (2015), two famous aviation companies GE avionics and Rolls-Royce were awarded for the contract phase 1 for exploring the concepts of developing critical components in the year of 2007. In 2009, phase

2 contract of continuing the testing of components of ADVENT engine equipments was issued for Rolls-royce. Developed technologies were to be experimented in form of prototype testing in demonstrator engine. Simultaneously GE avionics was awarded for the experiments on the core of the technology demonstration regarding efficient aircraft engine development. However this kind of contract phase awards were not expected as criteria the program of the ADVENT engine development states single contractor performance for the second phase of development. Hence the program was denied by US Air Force for creation of a backup engine development program (geaviation, 2017).

Pratt and Whitney has become able to invent a technology of obtaining adaptive variant of the fan speed optimization. In such cases, the design of geared turbofan serve the purpose of the design and development program associated with ADVENT engine. According to Guo and Thomas (2015), the discovery of Pratt and Whitney was considered under the program of Adaptive Engine Development (AETD) program. Hence, GE authorities selected to continue the work of ADVENT development under the program of AETD. In other words Pratt and Whitney eliminated Rolls-Royce in continuation of the engine development program under ADVENT. Operational testing of all the required engine components was started in the year of 2013.

Application of the ADVENT engine: Implementation of the ADVENT engine is still under research and development. This section of the dissertation will provide information regarding the expected application of the ADVENT aircraft engine. According to the primary objective of the ADVENT development program, the advanced engine was to be used in the Next Gen Bombers of US Air Force. Due to the misunderstanding in the contracts of phase 2, Rolls-Royce has become the primary developers for the project of optimizing engine speed with the fuel efficiency. Hence, according to the research work, the engine became suitable for the engine up gradation of potential 2020 engine of F-35 lightning 2. According to Guo *et al.* (2015), F-136 has been used for the alternative of F-35. This alternative solution was suggested by the development team under ADVENT project. After inclusion of Pratt and Whitney in the research work of ADVENT development program, the design became suitable for commercial purposes also.

Adaptive Cycle Engine (ACE) was also included in the program for engine development. According to the expected performance criteria under ADVENT program, iot is stated that 50 % of improvement in loiters time would be helpful in persisting longer time in certain areas of reduced risk factors. In order to make the pilots able to flight for longer time under certain complex situations with fewer risks, 35 % range is expected to be increased. Reduction in fuel consumption rate by 25 % is expected to increase the efficiency of the engine significantly. Advanced cooling technology attached with the ADVENT engine design would help in absorbing 60 % more heat compared to the conventional aircraft engines (Rolls-Royce, 2017).

Adaptive Cycle Engine:

Figure 2.4.2: Adaptive Cycle engine

(Source: geaviation, 2017)

This aircraft engine was developed under the researchers of GE Aviation. The primary focus of the research work on this engine can be stated as the increment of engine thrust generation capacity up to 20 % more than the traditional engine. According to Boyd (2015), increase in the fuel efficiency helps in having better heat dissipation capacity of the aircraft engine. ACE engine can be considered as the result of the research work under ADVENT program of engine development as it comprises with the optimization of the fuel economy and speed generation. More than $1 billion was invested for development of this engine. Implementation of this engine would require some advanced manufacturing process for obtaining the design criteria of ADVENT development program. Advanced design technology and improved additive manufacturing processes are expected to be used for commercialization of this engine application (geaviation, 2017).

2.6 Concept of open rotor

In avionics and aircraft designing, open rotor type engine is called as the prop fan engine. The concept is related to both the turboprop and turbofan. Design of the open rotor aircraft engine is concerned with the engine performance in terms of the angular velocity of the rotor, longitudinal velocity of the aircraft body and the efficiency of the engine in terms of fuel economy. In case of the manufacturing of short twisted propeller blade, prop fan is designed. The Fan structure and the design dimensions are similar to that of the bypass compressor fan blade. According to Angi and Huminic (2015), prop fan can be demonstrated as the unducted fan or a turbofan with high bypass. In case of open rotor engines, contra rotating stages of fan are not enclosed by a casing. The designs of the propeller blade in are prepared with close tolerance with the turbine fan blade in case of open rotor engine. According to united technologies, blades of small diameter and high load are incorporated with the open rotor engines in the aircraft driving system.

Development of open rotor

According to the history of the turbofan engines, it is found that the capacity of an open rotor engine was about 4710 lbf, which is equal to the value of 21,000 Newton force (Cox *et al.*, 2016). This prop fan was featured with twin contra rotating fans mounted at the rear part of the aircraft engine. Research work was started by Carl Rohrbach regarding the open rotor engine replacement in aircraft engineering. Former research work regarding the turbofan and turboprop were done under the research work of unducted fan engine. Similar electric propellers were used in those engines.

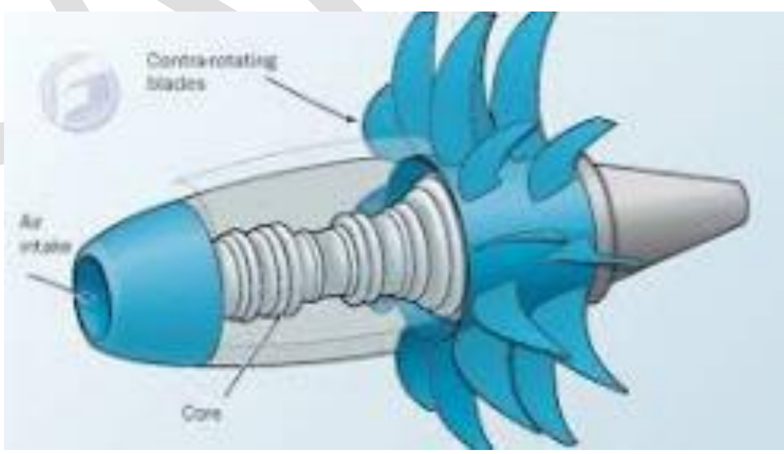

Figure 2.5.1: Open rotor

(Source: Cox *et al.*, 2016)

Concept of prop fan was developed in the year of 1970. Testing of several prop fan design prototypes was done after preparation of the engine design. Unducted fan GE36 was a variation of the design regarding the concept of prop fan. According to the basic design of the open rotor engine, it is stated that, the single propeller was driven by the basic jet open rotor engine through a gearbox. These kinds of engines were used in private low speed small aircrafts. Due to some unresolved technical issues, unducted fans are not produced commercially. Reduction of the fuel price became the only way of commercial advantages (Giazotto and Airbus Operations Ltd, 2017). In case of new aisle aircraft, the design of the open rotor engine can be considered with a complex replication of the turboprop and a configuration. New technologies are still under the process of research and development. Some of the following features are expected to be incorporated into the new open rotor engines. ***[Referred to appendix 3]***

- It should be incorporated into the advanced compressor and turbine system for better control. Improved aerodynamics is to be used for identifying the appropriate blade materials.
- Better cooling technologies are to be used for better engine performance under severe circumstances.
- Considering the environmental aspects regarding the engine exhaust in the emission, low emissive combustors are to be used. Combustors of novel lean burn type are expected to reduce the emission of the different nitrogen oxides by a significant percentage.
- Improvised electronic precision control systems are to be implemented in the design of the aircraft engine for smooth operation (Alonso-Miralles and Yu Rohr, 2017).
- Lightweight materials are preferable for producing engine parts in case of aircraft designing.
- In Order to optimize the performance of the propeller in all the possible flight conditions, improved pitch control and aerodynamics are to be used in the turboprop or turbofan engines.

Working of the rotor

Open rotor engine is considered as a turboprop engine with two separate sets of fan blades or propellers. This arrangement is expected to deliver higher rotary motion and aircraft speed than in case of conventional turboprop engines. The blades of the open rotor modified engine help in spin the air out rather than pushing the air back into the propeller arrangements. The rear set of fan blades suck the air generated due to the backward push of the forward propeller set. The air is actually entrained between the two separate sets of blades in this engine (Busch *et al.*, 2015). A concept of virtual fan case is applied with real implications. The first set of fan blades helps in stopping the pushed air, whereas the second set of the blades helps in straightening the streamline flow of the air. Hence the speed of the turbofan is increased than aircraft equipped with conventional turbofans.

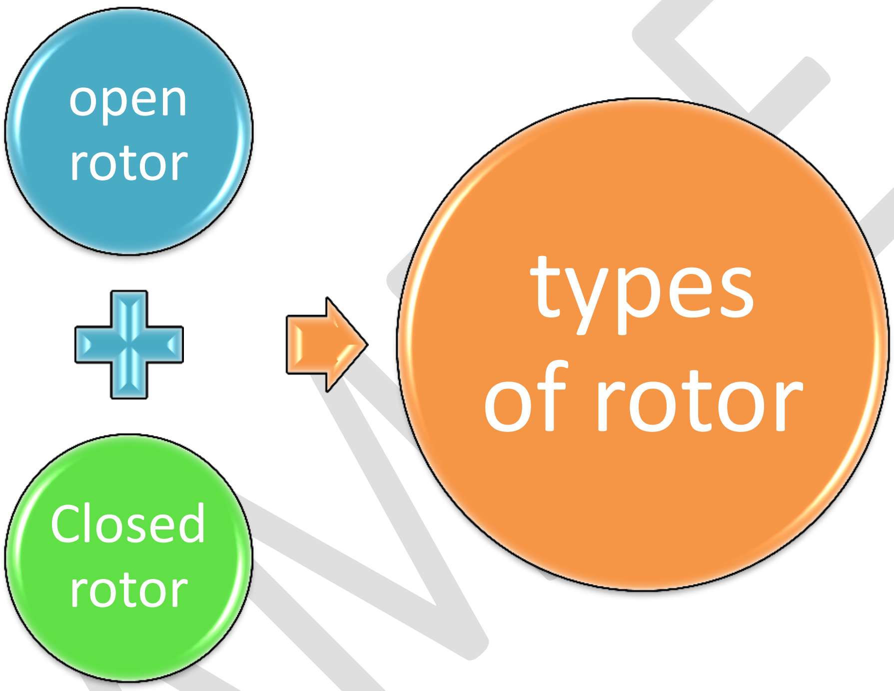

Figure 2.5.2: Types of rotor

(Source: Self created)

According to the experimented velocity of the prototype, the velocity of the real aircraft equipped with two phase turbofan-turboprop engine can be expected as 0.76 Mach number. The comparison of this speed is made in terms of the speed of jet powered aircraft M0.845. According to the dimensional requirement of the turboprop engine blades, it can be stated that the diameter of the blade is made with twice of the diameter of the open rotor engine blades for producing same amount of thrust force under similar circumstances (Paquet *et al.*, 2014).

Efficiency: Two types of efficiencies are calculated to refer the engine performance in case of turboprop engines. These efficiencies are thermal efficiency and the propulsive efficiency of the engine. Overall efficiency is calculated by multiplying these two efficiencies. According to Angi and Huminic (2015), thermal efficiency is calculated as the amount of energy generated per unit of fuel consumption. The propulsive efficiency of the turboprop engine is defined as the efficiency to obtain the thermal energy and to use for creating an aerodynamic thrust. This thrust is simply called as the 'push'. A single propeller is expected to produce 90 5 to 92 5 of the efficiency of propulsion. The value of peak efficiency drops with further increase of the aircraft speed.

Advantages and disadvantages of the open rotor

Advantages of turboprop engine can be stated as follows.

- In case of a modified open rotor or turboprop engines, noise has reduced significantly.
- Better containment is achieved regarding broken blades.
- This kind of aircraft engine is safer in case of ground operations while engine is running.
- Size of the propeller is comparably smaller than that in case of other engines. Hence space consumption of this kind of engines is less.
- The appearance of this engine is like fancy jet engine (Elving *et al.*, 2015).

Disadvantages of this engine are stated as follows.

- In case of lifecycle cost, no thrust reservoir, fan case or the nacelle is attached to the turboprop engines.
- Efficiency is less. Several research works are going on to increase the efficiency.
- Additional frictional drag and the weight are problematic.

2.7 Concept of gearing fan and its implementation

The geared turbofan engine is considered as comparably more efficient aircraft engine than the conventional turbofan aircraft engine. Different ranges of angular velocities are obtained in the assembly of the compressor and turbine.

Implementation of planetary gearboxes in aircraft engines

In order to increase the engine efficiency of the commercial flights, planetary gearboxes are introduced in the engine assembly. According to Pourbabaee *et al.* (2016), in case of introduction of a geared fan, environmental and safety factors are considered. The safety and environmental standards of using planetary gearboxes in the aircraft engines are determined by the organization

ICAO. Introduction of gearbox into the aircraft engines reduces the number of dismantled moving parts.

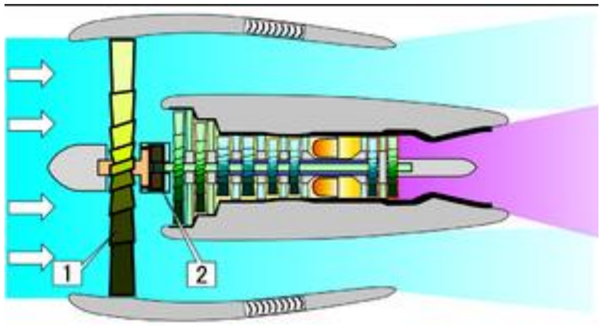

Figure 2.6.1: Geared turbofan

(Source: Pourbabaee *et al.*, 2016)

Optimization can be easily done by using the different required angular velocity of each of the engine propellers and the engine shafts. Hence efficiency of the engine increases up to a certain percentage. Other than the rate of fuel consumption, it also becomes more eco-friendly as the exhaust that comes out from this engines is less toxic. Amount of exhaust emission is also reduced using geared fan in the aircraft turbofan engines. In future, the geared turbofan is expected to replace the conventional turbofans due to its greater economic benefits, efficiencies and increased sustainability factors.

Difference between geared turbofan and conventional turbofan

- The primary difference between conventional turbofans and the geared turbofan can be stated in terms of fan blade diameter. Longer fan blades are used to for the purpose of taking a greater volume of air into the engine.
- In case of geared turbofan, a number of moving parts is significantly less than the conventional turbofans (Brady *et al.*, 2016).
- In the geared additional planetary gearbox is mounted with the primary rotating engine shaft in order to have a different velocity of the arrangement of different sets of fans according to the requirement. In a conventional turbofan, no such gearbox is attached to the main engine shaft.

- In case of geared turbofan, a larger amount of thrust force is generated due to a greater volume of intake air through the engine propellers. Hence propulsive efficiency of the geared turbofan is found to be greater than the conventional turbofan.
- The weight of the geared turbofan has been found to be less than that of the conventional one due to a lesser number of parts in the assembly of geared fan engine.
- Both the compressor and turbine blade speed are optimized by the gearbox attached between them. This technique can be considered as the primary way to increase the efficiency of the conventional engine by a significant percentage.

Recently, a deal has been signed with spirit airlines by Pratt and Whitney (major turbofan manufacturer) for implementation of the geared turbofan (Edelson *et al*., 2015). During prototype testing of the geared turbofan, different advantages were found, which seems to be enough to replace the conventional turbofan from the aircraft engine design.

Advantages of geared fan engines

1. Greater efficiency
2. Lower fuel consumption
3. Economical benefits
4. Induced sustainability
5. Less noise
6. Reduction of engine emissions.

2.8 Concept of LEAP

Leap in engine was first commercially produced by CFM international aircraft engine manufacturing company. Leap engine is a kind of high bypass turbofan type engine. This was a joint venture of two prominent aircraft engine manufacturing company GE aviation, CFM international and Saffron engines. This engine is considered as the successful replacement of the CFM56 engines. This Leap engine creates a tough competition for the introduction of highly efficient geared turbofan proposed by Pratt and Whittney. Introduction of the leap engine brings revolution in the market of jetliners.

Design

Basic architecture of the leap engine involves a simpler version of the low pressure turbines used in genx aircraft engines. Flexible fan blades are used in this kind of engines. Material used for manufacturing the blade is transfer molded resin. This material is used to untwist the fan blade as the increase of the angular velocity of the fan shaft. In order to attain higher service life and the materialistic durability, maximum operating pressure is lowered by a significant factor of safety with a significantly larger value than in case of CFM56. A blisk fan, prepared from composite materials used in the compressor of the leap engine. As argued by Guo and Thomas (2015), bypass ratio of 10:1 is obtained due to use of the blisk fan during takeoff and landing. The most suitable materials for the production of turbine shrouds are found to be ceramic matrix composites (CMC). ***[Referred to appendix 1]***

Figure 2.7.1: Leap engine

(Source: Guo and Thomas, 2015)

Inclusion of these kind of manufacturing materials for production of leap engine helps in reducing the weight of the engine and it also helps in reducing the rate of fuel consumption by 16 % (Guo and Thomas, 2015). An advanced educator based oil cooling system is incorporated into the system of the engine cooling. In this engine cooling system, coolers are mounted on the fan duct within the inner lining. This mounting helps in keeping the oil pressure up to a desirable level.

Design and Development

According to the structural design of the leap engine, several parts can be identified. The casing of the leap engine is a solid structure with a 360 degree HPC double wall casing. The portion of the direct drive ensures the high bypass ratio of the engine with reduction of engine noise. Errorless mounting and good alignment helps in reducing the noise. Fan casings and blades are produced from lightweight durable composite materials. In this engine high-pressure multistage compressors are used with 10 compressing stages. It increases the pressure ratio up to 22:1. Hence it becomes easily operable (Cadorin and Zitoune, 2015). At the end of lean burn compressor, the turbine is attached to a system of advanced cooling.

Advantageous features

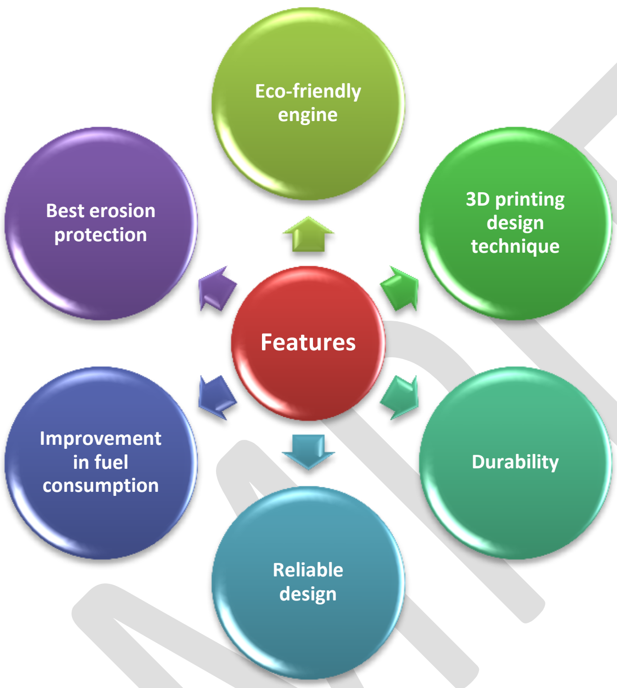

Figure 2.7.2: Advantageous features

(Source: Self created)

Improvement in fuel consumption and efficiency: According to the specifications of the leap engine, it can be coined that rate of fuel consumption is 15 % lesser than that of the current best aircraft engine CFM56 under similar circumstances without compromising with the reliability factors and safety factors (Boyd, 2015). Life cycle and the additional maintenance cost is also less compared to those of the CFM56.

Reliable design: leap engine is said to be serving 99.98 % of dispatch reliability after perfect manufacturing (Cadorin and Zitoune, 2015). High reliability ensures good flight hours per maintenance time. It enables the better performance of the engine with commercial interpretation

Durability: Durability of this engine is better than that of CFM56 due to its robustness and working ability. Its light weight is also responsible for obtaining better durability. Lightweight manufacturing and design material for aircraft leap engine construction are selected as resin transfer molding (RTM). This is a type of carbon fiber composite that increases the durability of the engine assembling parts. Blade materials are strong and flexible enough to support the entire weight the aircraft. Weight of the engine is defined as less than 500 lbs (Quintero *et al.*, 2017)

3D printing design technique: In leap engine manufacturing, Grow complex is used to obtain additive manufacturing. This process helps in preparing dense but lighter engines. Nozzles of the fuel are expected to 25 % lighter than that of the previous gas turbine or open rotor engine models (Fellet and Rossner, 2015).

Eco-friendly engine: Model of the combustion chamber used in leap engine is stated as premixing, twin annular swirler combustion (TAPS II). It helps in reducing the rate of emissions peer engine significantly with a percentage of 25 (Boyd, 2015). According to the working principle of this type of combustion chamber, it is stated that air-fuel are premixed before entering into the combustion chamber to reduce the quantity of the unburnt or partly burnt particles that creates pollution. Hence it tends towards the complete combustion.

Best erosion protection: Debris rejection system involved in the leap engine provides the best way of protecting erosion of the engine parts. It prevents dirt, sand and other solid particles from reaching the core engine portion. Hence durability of the engine parts increases.

Specification

Expected specifications can be produced in form of a table.

Specification Type	**Expected specification of LEAP 1A, 1B, and 1C**
Configuration	Twin spool turbofan
Turbine	High pressure turbine of 2 stage and low pressure turbine of 7 stage
Overall pressure ratio	40 : 1
Compressor	Second generation swirler combustor with pre-mixing and twin annular specification
TSFC	Negative 15 %

Diameter of the fan	Average of 78 inches
Bypass ratio	Average of 10 : 1

Table 2.7: specification of leap engine

(Source: Brady *et al.*, 2016)

Dimensional specification can be provided in terms of average expected length of the engine, maximum height and weight of the engine. Length is about approximately 3.328 m. Maximum height is about 2.256 m (Brady *et al.*, 2016).

2.9 Summary

This chapter is provided to include all the possible data regarding the research topic for obtaining a specific research platform. In this chapter, aircraft engine design is described with evolutionary aspects of aircraft engines. Gas turbine aircraft engines are discussed in terms of advanced modification implemented with it to increase the efficiency of the engine. Besides this, some advanced aircraft engines like Turboprop and turbofan engine, geared turbofan and leap engines are also discussed in terms of expected specification and implementation. Possible advantages and disadvantages of these engines are also provided to ensure regarding the sustainability factors in the commercialization of these engines. Environmental and commercial aspects are also considered with the technical interventions of these engine designs.

CHAPTER 3: METHODOLOGY

3.1 Introduction

Research methodology chapter of a scientific dissertation can be considered as the science of continuing a research work by selecting appropriate methodological tools to serve the purpose of the research work. It helps in solving the problems related to the research objectives in a systematic manner. Suitable methodologies are used to be able to answer all the predetermined research questions. The research work should be able to describe and explain the entire research question coined at the beginning of the research. In this chapter methodological tools of different types like philosophy, research approach, and research design are selected as per the research requirement.

3.2 Method Outline

Method Head	**Chosen methodology**
Research Philosophy	Positivism
Research Approach	Deductive
Research Design	Descriptive
Data Collection process	Secondary quantitative and qualitative analysis
Data Analysis process	Statistical and qualitative thematic analysis

Table 3.1: Research outline

(Source: self created)

3.3 Research onion

Research onion is stated as the framework regarding different methodological layers of the research works. According to Saunders *et al*. (2010), it includes different layers like research strategies, research techniques, time horizons, choices, research design and philosophical approach. All the layers of the research works are tried to be followed by the researcher during performing this research work regarding the development of advanced aircraft engines along with a consideration of technical, environmental and commercial aspects.

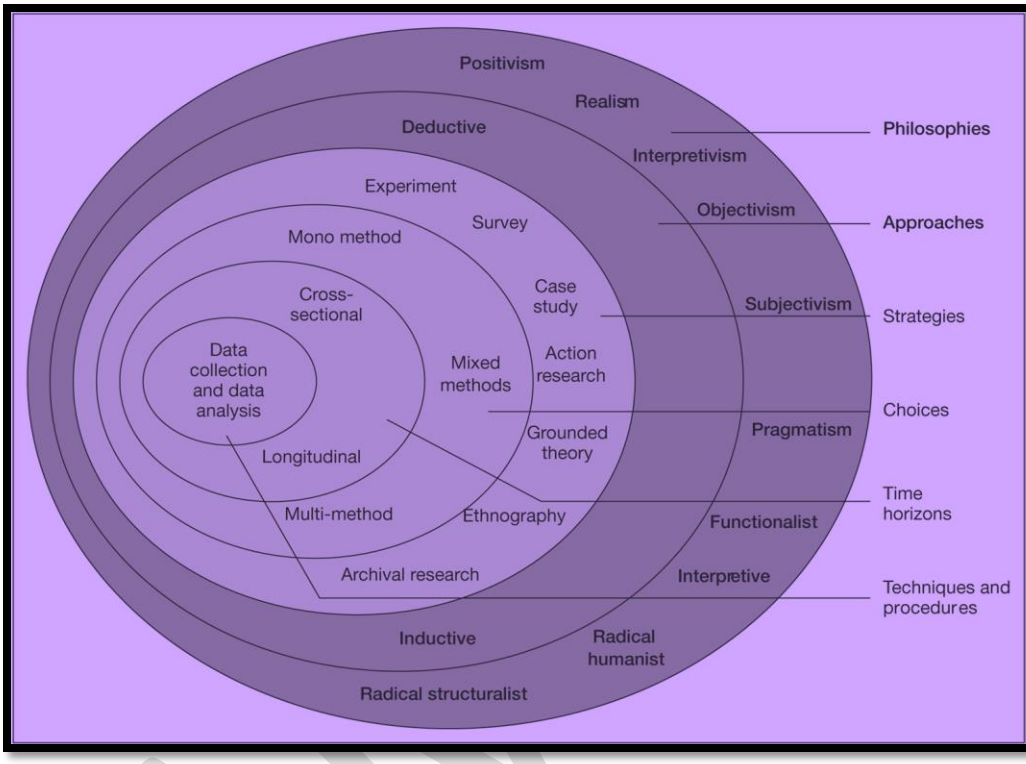

Figure 3.3: Research onion

(Source: Saunders *et al*., 2010)

3.4 Research philosophy

In case of scientific research works, three research philosophies are available. These are positivism, realism, and interpretivism. In case of positivism philosophy, testing of a developed hypothesis is performed according to the research demand. As opined by Kothari (2004), logical and meaningful arguments are considered for obtaining a specific conclusion regarding the research questions and objectives. Interpretivism research work is completely based on the observation of the collected data and the interpretation of the viewpoints from different perspectives of researchers and other relevant people are considered. In case of realism philosophy, socially accepted truths are used as the source of reliable data. Positivism research philosophy has been selected as the appropriate one for this scientific and technical research work.

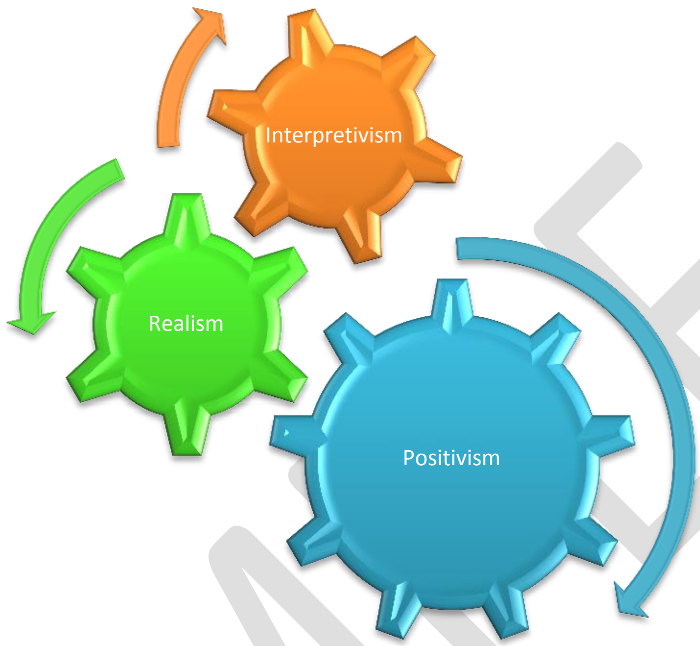

Figure 3.4: Research philosophy

(Source: Self created)

3.4.1 Justification of selecting positivism philosophy

In this research work, different data are collected based on the expected value of the engine parameters. Expected values are collected from prototype testing. Possible arguments regarding efficiencies of several advanced aircraft engines are to be analyzed rationally and technically to ensure the sustainability of the engine designs in aircraft manufacturing industry and airline industry. Hence positivism philosophy seems to be the most appropriate philosophy for this research work due to its nature of logical and rational arguments.

3.5 Research approach

Two types of research approaches are mainly used in research works. These approaches are inductive and deductive research approach. According to Yin (2013), the primary purpose of selecting a suitable research approach is to be able to answer all the research questions after completion of the research work by means of systematic analysis and revision of the background studies. In case of inductive research approach, certain hypothesis is to be formed and a certain specific pattern is to be drawn from the obtained data collected from secondary or primary data resources. In case of deductive approach, no such hypothesis is formed. Answering the research question is the primary concern.

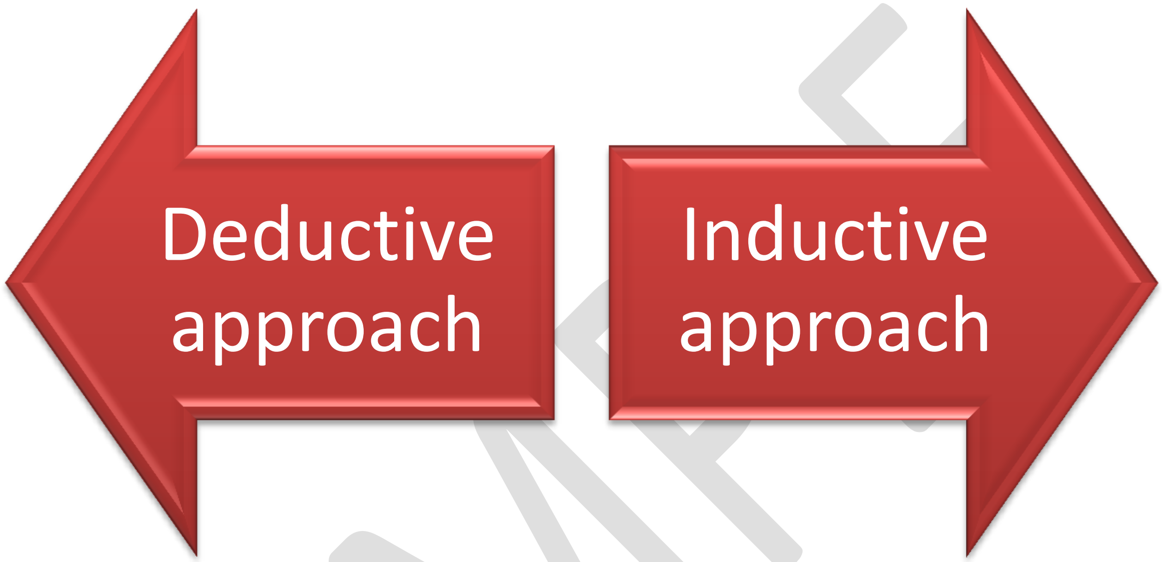

Figure 3.5: Research approach

(Source: Self created)

3.5.1 Justification for selecting deductive research approach

The research work regarding the study of development of advanced aircraft engine design does not incorporate with inducing certain new set of hypothesis. Rather than this, all the research questions are to be analyzed to achieve the research objectives in an effective way. Hence deductive research approach is applicable to this scientific research study.

3.6 Research design

Available research designs are of three types. These are descriptive, explanatory and exploratory. According to Kothari (2004), descriptive design of the scientific dissertation focuses on the systematic information sets, which are sequenced in such a manner that would help in answering all the research questions with satisfactory interventions. Explanatory research design is used for finding the cause and effect relationship among the relevant research variables. In case of exploratory research work, background information is considered as the primary focus of the research work. In order to fulfill the research requirements, descriptive research design is selected in this dissertation.

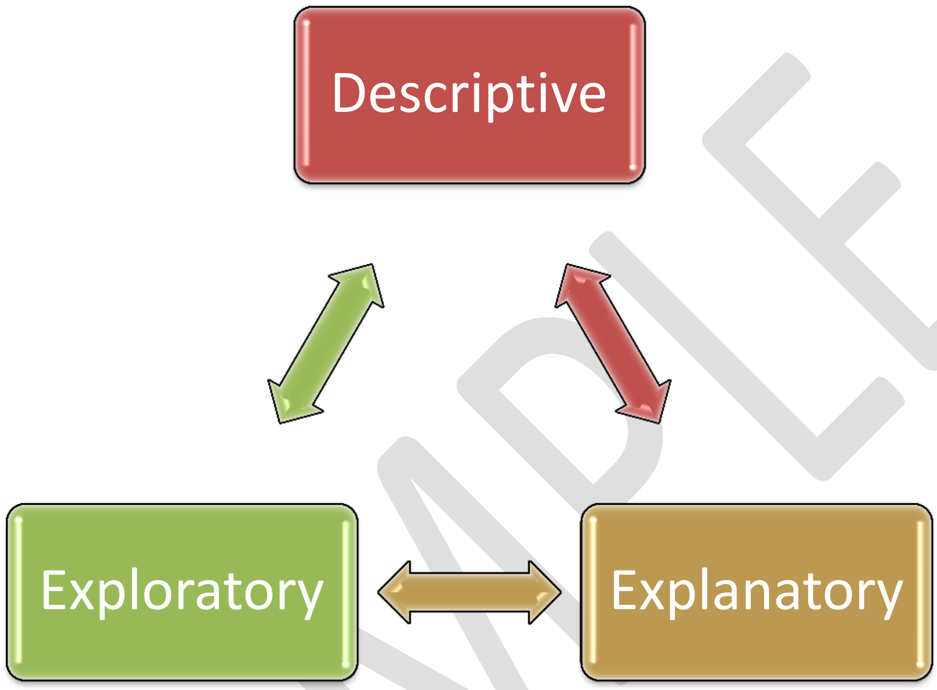

Figure 3.6: Research Design

(Source: Self created)

3.6.1 Justification for selecting descriptive research design

Descriptive research design concentrates on describing the facts and phenomena in detail and logical studies. In this research study, highly advanced aircraft engine is required to be studied and focused with detailed expected specification in order to obtain the sustainability factor of these engines in aerospace engineering. It does not any cause and effect relationship between different research variables as the majority of this research study portion focuses on the design of advanced aircraft engine. Hence descriptive research design seems to be most suitable for this study.

3.7 Research strategy

According to the requirement of the scientific research strategies, four types of research strategies are mainly used to perform the research work efficiently. These strategies are action research, case study, interview and survey. In case of this research work, action research strategy can be used. In this research study, implementation of advanced more efficient aircraft engines is of primary concern due to the issue of higher fuel consumption of the conventional aircraft engines. It is expected to find the possible solution regarding the problems of the commercialization of some of the conventional engines due to a higher rate of fuel consumption and high rate of fuel price. Action research strategy is the only strategy that would be helpful in meeting the research requirements regarding solving the issues by obtaining the implementation of advanced efficient aircraft engines.

3.8 Data collection techniques

In Order to achieve the research objective of this research work, two types of data are available in the data resources. Both qualitative and quantitative data are collected in order to have a transparent idea regarding the research subject involving the working principles and specification of the advanced aircraft engines. According to Yin (2013), in case of qualitative data, non numeric technical data are collected for further analysis regarding the technical and environmental aspects. In order to consider the commercial aspects with the technical data, quantitative data sets regarding specification, expected power, cost values ar collected. In the data analysis chapter, both qualitative and quantitative collected data are to be analyzed to provide specific recommendations for effective implementation of some advanced aircraft engines like geared turbofan or leap engine.

In order to collect desirable data from the data collection resources, primary and secondary resources are available for research study. In case of this study, required data are collected from secondary data resources like some online articles, online books, journals and websites of some aircraft manufacturing companies. In case of preparing some specification chart, secondary databases, graphs and experiment results are obtained.

3.9 Data analysis plan

According to the research requirements, secondary thematic analysis is done to attain success according to the research aim. Quantitative data are analyzed by expressing it in form tables and charts to obtain possible analysis. In order to have critical analysis of the qualitative data, these data are sequenced in a proper sequenced way. Sequencing the data will help in finding the loopholes in research work and the collected datasets. Statistical tools like medians root mean square averages and standard deviations are used for thematic analysis of the quantitative data. Microsoft Excel can be used as the tool for expressing the statistical graphical form.

3.10 Ethical consideration

During performing the research works, certain codes and ethical principles are required to be followed by the researcher. No personal information is to be collected without the permission of the information owner. In case of collecting secondary data, inaccessible websites should not be used without the permission of the authority of the selected company. Collected data should not be used in personal profitable activities other than this research work according to the data protection act 1998. Data should be collected only for the purpose of academic research works. Copyright rules are not to be broken during conduction of the research work. Proper respect is to be produced to the source of the information by means of in texting according to the matter requirements.

3.11 Time plan

Name	Duration	Start	Finish	Predecessors
Indetification of Topic	15 days	12/20/17 8:00 AM	1/9/18 5:00 PM	
Identification of Possible Issu	10 days	1/10/18 8:00 AM	1/23/18 5:00 PM	1
Development of Aims and C	15 days	1/24/18 8:00 AM	2/13/18 5:00 PM	2
Review of exiting literature:	20 days	2/14/18 8:00 AM	3/13/18 5:00 PM	3
Selection of research metho	15 days	3/14/18 8:00 AM	4/3/18 5:00 PM	4
Collection of data	10 days	4/4/18 8:00 AM	4/17/18 5:00 PM	5
Analysis of Collected data	15 days	4/18/18 8:00 AM	5/8/18 5:00 PM	6
Proving recommedations	10 days	5/9/18 8:00 AM	5/22/18 5:00 PM	7
Drafting	10 days	5/23/18 8:00 AM	6/5/18 5:00 PM	8
Final Proofread	5 days	6/6/18 8:00 AM	6/12/18 5:00 PM	9
Submission	1 day	6/13/18 8:00 AM	6/13/18 5:00 PM	10

Figure 3.11: Research time plan

(Source: Self created)

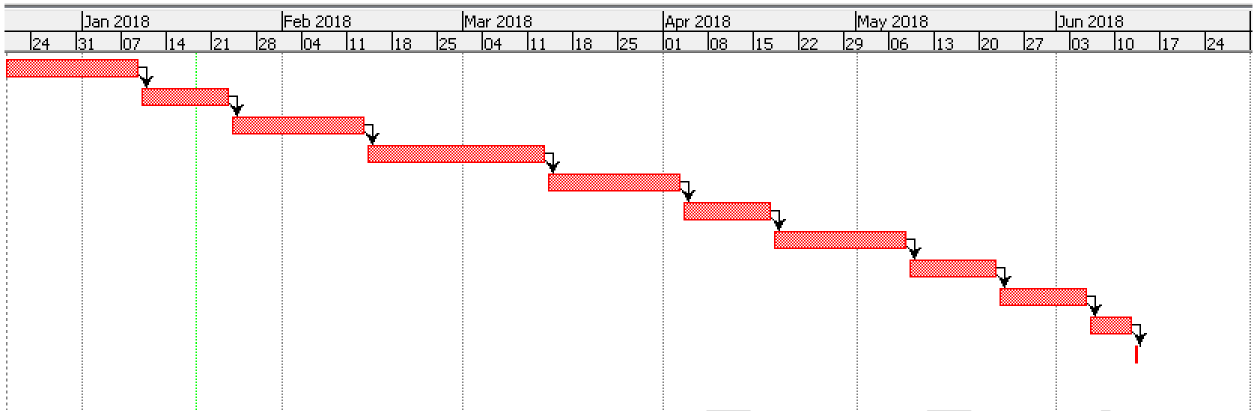

Figure 3.11: Research time schedule

(Source: Self created)

3.12 Summary

This chapter can be summarized as the collection of selected methodological tools. In this chapter, different techniques are analyzed and selected as the result of evaluation. In order to obtain the research objective effectively, deductive research approach has been selected. According to the availability of the research design for scientific research approach, descriptive research design is selected as the most suitable design for this research work. Positivism research philosophy has been applied in this research study for obtaining the research objectives. According to the research requirement, qualitative and quantitative data are collected from the secondary data research. Thematic analysis of the data is to be done in the next chapter in order to provide possible technical recommendation regarding development of the advanced fuel economy aircraft engines with higher efficiency than the traditional engines.

CHAPTER 4: DATA FINDINGS AND ANALYSIS

4.1 Introduction

In this chapter of this research work, researcher is about to provide the possible interpretation of the collected technical qualitative and statistical data from the secondary resources in order to achieve the research objectives. Relationship between different variables of this research subject is to be analyzed in order to answer all the research questions with rational explanation. Several specification charts of the high efficient modern aircraft engine will be analyzed in this chapter of the dissertation in terms of several themes. Gas turbine engines, ADVENT operated antiskid braking system, efficiency of open rotor engines, geared turbofan engines, and leap engines are to be analyzed in this chapter. Analysis and the explanation would involve all the commercial, economic, environmental and technical aspects of the aircraft engine design. Quantitative analysis would provide analysis regarding efficiency, cost, and dimensional characteristics of different aircraft engines. Qualitative analysis will involve analysis of the qualitative data regarding the maintenance requirement, quality of the engine material and other nonnumeric mechanical characteristics.

4.2 Quantitative analysis

4.2.1 Theme 1: Analysis of the specification of gas turbine engine

Findings: According to the specification of the gas turbine engine, material cost for the single unit engine production, 10,000 $\mathcal{RM}$. Material cost for Junker piston engine was 35000 $\mathcal{RM}$. Operating angular velocity of the rotary part of the gas turbine engine assembly can be stated within a range between 10,000 rpm to 500,000 rpm. According to the MIT's millimeter-sized prototype specification, 500- 700 W.h/kg power are delivered for shorter terms. In case of longer terms, the value of generated power rises up to 1200 to 1500 W.h/kg (Kuz'michev *et al.*, 2014). According to the experimented value of this kind of aircraft engine run by simple thermodynamic cycle, efficiency gives a value near to 46 %. In case of combined engine, the value rises up to 61 %. Average value of the compressor ratio is 18: 1.

Specification	Value
Material cost	10,000 $\mathcal{RM}$
Operating spinning velocity of the rotor	10,00 rpm to 500,000 rpm
Power generation (In short term)	500- 700 W.h/kg
Power generation (In long term)	1200 to 1500 W.h/kg
Simple cycle efficiency and combined cycle efficiency	46 % and 61 %
Average compression ratio	18 : 1

Table 4.2.1: Specification of gas turbine engine

(Source: Kuz'michev *et al.*, 2014)

Analysis: from the collected data, it can be identified those traditional gas turbine engines mounted in aircrafts were not very much efficiency and fuel economy. Compression ratio was greater compared to other advanced aircraft engines like leap engine or geared turbofan engine. According to the experiment of the prototype testing in MIT, the generation of power was remarkably good in case of long term application. Material cost for production of the gas turbine engine parts was found to be reasonable compared to piston cylinder engines. Number of moving parts in gas turbine is greater than the piston engine but, the design of gas turbine engine is simpler.

4.2.2 Theme 2: Analysis of the specification of the open rotor engine

Findings: According to the design characteristics, specification of the open rotor system can be analysed. Lots of modifications have been obtained in design characteristics. A brief comparison of traditional and modified open rotor engine is provided here.

Parameters	Conventional open rotor engine	Modified open rotor engine
Blade count	12 * 10	12 * 10

Disk loading in point design (Hp/ft square)	100	59
Rotor diameter (ft)	10.7	14
Spacing diameter ratio	0.28	0.27

Table 4.2.2.1: Comparison of open rotor engines

(Source: Rolls-royce, 2017)

According to the strategy regarding power management, blade angle is estimated in relation to the velocity of the aircraft in terms of Mach number. The requirement of the blade angle possesses different short range for different aircraft velocity requirements. According to the graph presented for evaluating the blade angle in accordance with the Mach number, it can be stated that for Mach number about 0.2, required blade angle lies between 30 degrees to 40 degrees. With the increase in required Mach number, blade angle requirement also increases. In case of Mach number about or above 0.6, required blade angle rises from 45 degrees up to 65 degrees (Rolls-royce, 2017).

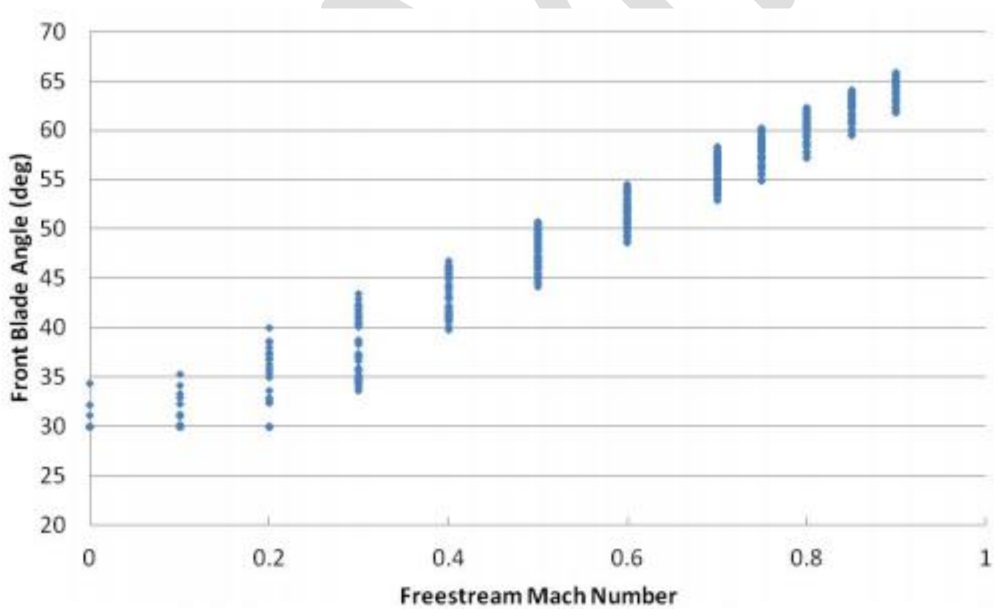

Figure 4.2.2: Blade angle vs Mach number

(Source: Aircraftsystems, 2017)

According to the specification of estimation regarding the efficiencies of different open rotor components, a specification chart can be provided. In case of open rotor engine 2 compressors and 3 turbines are used for obtaining overall propulsion efficiency. Efficiency of the each component can be provided in form of table.

Parts of open rotor	Parameters	Value
Low pressure compressor	Pressure ratio Isentropic efficiency in %	4.2 : 1 89.6
High pressure compressor	Pressure ratio Isentropic efficiency in %	10 : 1 88.6
Low pressure turbine	Efficiency in %	94.2
High pressure turbine	Efficiency in %	91.9
Power turbine	Efficiency in %	94.0

Table 4.2.2.2: Components of open rotor engines and efficiencies

(Source: Rolls-royce, 2017)

Other than this, another specification factor of generated operating thrust can also be presented in form of a table in order to provide a brief idea regarding its performance characteristics.

Performance parameters	Rolling takeoff
Net thrust in lbf	19000
TSFC in lbm/hr/lbf	0.229
Propeller thrust in lbf	18600
Exit temperature of combustor	3460 degree F

OPR	28.5

Table 4.2.2.3: Components of open rotor engines and efficiencies

(Source: Fellet and Rossner, 2015)

Relevant analysis can be obtained from the collected data sets regarding the performance and technical specification of open rotor engine.

Analysis: According to the collected data regarding the specification of the open rotor engine, it can be understood that, after obtaining modification, its operational characteristics have improved remarkably. Flexibility in choosing the blade angle helps in obtaining different aircraft speed requirements. Somehow from the application of different blade angle introduce the realization regarding the need of geared fan in aircraft engine. According to the collected data regarding the efficiency of the associated components of open rotor engine system, overall efficiency can be calculated by multiplying all the component efficiency value. It would give a value near about 65 %. According to the requirements modern flight engines, its efficiency is much below than the desired value. That is why lots of improvisation of this kind of engine is under research working focusing on the strategies for improving the efficiency.

4.2.3 Theme 3: Analysis of the specification of geared turbofans

Findings: Geared turbofan is considered as the modified version of the conventional turbofan by initiating it with an additional gearbox. The main reason behind implementing this gearbox between compressor and turbine and in other zones is to obtain different spinning velocity of different set of fan shafts attached with the compressor and the turbine according to different speed requirements (Boyd, 2015). The variation in speed is achieved by using gear ratio of the gear train included in the gearbox. According to the dimensional specification of geared fan turbofan, following table can be achieved for model PW1100G.

Specification	Value
Fan diameter	81 inches for 20 blades

Length	3.401 m
Weight	6300 lb
Diameter of the fan case	87.566 inches

Table 4.2.3.1: Specification regarding dimension of geared turbofan

(Source: geaviation, 2017)

This table produces an overall idea regarding the size and shape of the gear turbofan engine propellers and casing. According to the performance characteristics

This table produces an overall idea regarding the size and shape of the gear turbofan engine propellers and casing. According to the performance characteristics, it can be represented below.

Parameters	PW1124G
Bypass ratio	12: 1
Take off thrust (lbs)	23,500
Flat- rated temperature, (degree c)	ISA + 15

Table 4.2.3.2: Specification regarding performance of geared turbofan

(Source: geaviation, 2017)

According to the facts of the geared fan design, three types of gearbox designs are used in experiments for obtaining required speed ratio from the selected gear train. In case of star gear train, carrier frame is fixed with the input sun gear and output ring gear. Gear ratio for this kind of design can be in the range of 2:1 to 11:1 in opposite direction. In case of the planetary gear train, ring gear is fixed with input sun gear and output carrier frame. Gear ratio for this kind of design would be in the range of 3:1 to 12:1 in the same direction. In case of solar gear train, sun gear is fixed with input ring gear and the output carrier frame. Gear ratio for this design would vary in the range of 1.2:1 to 1.7:1 in the same direction (geaviation, 2017).

Analysis: Dimensional specification of the geared turbofan reflects its size and shape and the required floor space for proper manufacturing. In case of geared turbofan, some additional space is required to adjust the gearbox. Due to the compactness of the turbofan design, the space required is minimized. High bypass ratio of geared turbofan improves its thrust generating performances. It helps in generating about 23500 lbs takeoff thrust according to the requirement of the entire aircraft based on the weight and number of engines of the aircraft (Despeisse and Ford, 2015). In case of star gear train, due to rotation of the gears in opposite direction, a balance in torque is obtained. Stress generation is supported by the planetary and solar gear train design due to the tough joints between carrier frame and the planet gear. According to the system requirements of generating thrust in the aircraft engine, several specific numbers of gearing discs are designed to optimize the speed of the rotor of the compressor and the turbine shafts.

4.2.4 Theme 4: Analysis of the specification of leap engine

Findings: Based on the experimental results of the small size leap prototypes, several types of leap engine specification set is expected from the Leap 1 A, Leap 1 B, and Leap 1C. According to the type of requirements of specific aircrafts, different leap engine can be used. Comparisons between their dimensional specifications are coined below in tabular form.

Parameters	**LEAP 1A**	**LEAP 1B**	**LEAP 1C**
Fan diameter	78 inch	69.4 inch	78 inch
Length of the engine	131 inch	123.9 inch	177.4 inch
Bypass ratio	11:1	9:1	11:1
Maximum allowable width	99.7 to 100.1 inch	95.3 inch	104.7 inch
Maximum allowable height	93.2 to 93.9 inch	88.8 inch	106.9 inch
Expected weight of the engine	6592 to 6951 lb (Wet weight)	6130 lb (dry weight)	8675 lb (Wet weight)

Table 4.2.4.1: Specification comparison of Leap engines

(Source: cfmaeroengines, 2017)

Performance characteristics are also comparable between the types of leap engines. According to the parameters based on the engine performance, a table of comparison can be provided.

Parameters	**LEAP 1A**	**LEAP 1B**	**LEAP 1C**
Take off thrust	106.89 kn	160.41 kn	129.98 kn
Maximum continuous thrust	104.58 kn	127.62 kn	127.98 kn
Maximum adjusted rpm of the fan shaft	Low pressure turbine: 3894 rpm High pressure turbine: 19391 rpm	Low pressure turbine: 4586 rpm High pressure turbine:20171 rpm	Low pressure turbine: 3894 rpm High pressure turbine:19391 rpm

Table 4.2.4.2: Performance comparison of Leap engines

(Source: cfmaeroengines, 2017)

According to the configuration of the specification related to the type of turbofan engine, in all of the leap engines, twin spool turbofan is used with high bypass ratio about average of 10:1. Operating pressure ratio is recorded in the experiments of Leap prototype testing as 40:1 (Fellet and Rossner, 2015). As per the engine specification of generalized leap engine, the multi-staged compressor is used with 3 stages for low pressure compressor and 7 stages for high pressure operations.

Analysis: According to the comparison regarding the performance and dimensional characteristics of three types of leap engine, length and width of the Leap 1B engine is less. Dimensional analysis of this engine can reflect that Leap 1b engine is more compact in design than remaining two types of the engine. Dry weight of this engine is also recorded as the lowest value. Compactness of this engine helps in minimizing the space requirements in the aircraft body. Light weight of this engine can reflect its greater efficiency in generating the required amount of thrust by consuming the lowest amount of fuel. According to the performance analysis of these three types of aircraft leap engine, for high speed small aircrafts, Leap 1b can be most effective. In case of large commercial aircrafts Leap 1C and Leap 1A can be used. Dimensional specification and performance criteria are comparable for Leap 1A and Leap 1C. Leap 1B seems to have the most effective feature in the aircraft industry.

4.2.5 Theme 5: Analysis of the specification of ADVENT

Findings: ADVENT engine can be considered as the next generation engine design and development for obtaining a significant improvement in efficiency of the traditional aircraft engine. According to the expected features and criteria of the ADVENT engine design, some performance characteristics can be shown in form of table. ***[Referred to appendix 4]***

Parameters	Change
Loiter time	50 % improvement is expected in the realm of loiter time in case of using ADVENT engines for aircraft in a commercial way.
Range of flight	Range of flight is expected to be increased up to 35 % than before. Due to higher flexibility of the range of flight. Longer flight times are expected in severe scenarios.
Rate of fuel consumption	25 % of reduction in the rate of fuel consumption is expected from the new next-generation ADVENT engines.

Table 4.2.5.1: Performance of ADVENT engines

(Source: Rolls-royce, 2017)

Analysis: According to the performance criteria of the next generation ADVENT engine developed under the department of US defense, efficiencies are expected to be rose significantly. This engine combines with the adaptive cycle engine. It will help in reducing the rate of fuel combustion because of light weight, high efficiency engine and capability of creating a greater amount of thrust. Performance criteria clearly reflect that this engine is going to be used for security purpose of the country in the defense. This engine is able to direct the majority of the air through the core fan streams of the engine. Thus greater amount of thrust is generated.

4.3 Qualitative analysis

In the qualitative analysis section of this dissertation, material requirement, and other material criteria are to be analysed considering commercial, environmental and technical aspects. Sustainability factors of engine designs are also included in this analysis portion.

Findings: In case of designing an aircraft engine, material requirement concentrates on the factors of stress and strain generation on the blade of the turbine and compressor rotors and the blades. According to the practical assumption of the aircraft engine design, temperature of the turbine inlet exceeds 1200 degree c (Cox *et al.*, 2016). This portion of the engine is considered as the hottest part of the gas turbine engine. According to the design requirement of the engine blades, mid-span of the airfoil is the most fracture prone zone due to the less stress allocation during running period of the engine. The entire centrifugal load is beard by this airfoil root section. According to Wohlers and Caffrey (2013), possible factors of failure are to be considered during designing the blade of the aircraft engine turbine and compressor. Possible failures of the blades are creep failure, rapture, fatigue failure, failure due to corrosion in the tip and edge of the airfoil. Engine materials can be some alloys containing different inorganic materials like Co, Cr, Al, Ti, Nb, Mo, W, Hf, C, Fe. According to the composition of the alloys, Cobalt, Aluminum and Chromium are the most used inorganic materials.

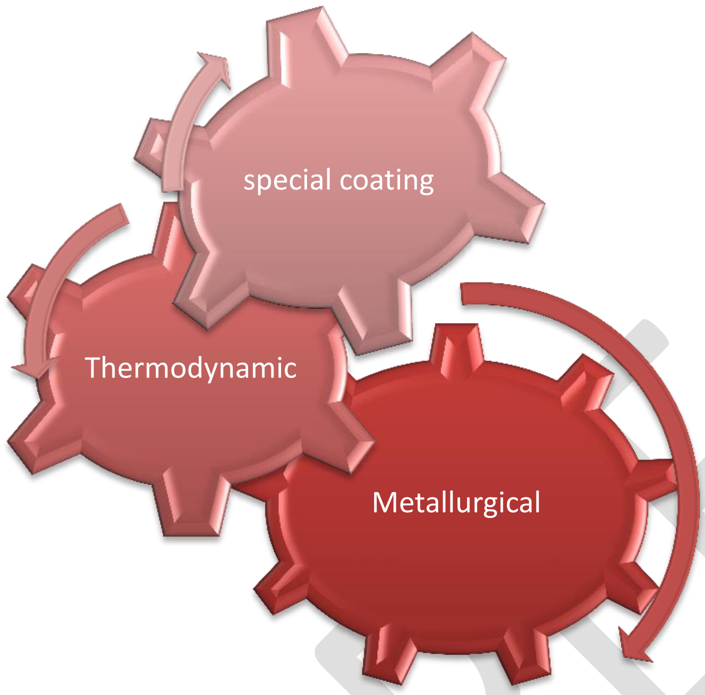

Figure 4.3: Performance of improvement techniques

(Source: Self created)

Complementary techniques of increasing the durability of the aircraft engine can be provided as follows. Metallurgical principles help in applying the more stable, high strength, temperature resistant material in producing the engine blades. The second technique uses thermodynamic properties regarding the efficiency of the engine to reduce the rate of fuel consumption. Proper engine cooling techniques, recycling unburnt fuel particles are important techniques to improve the efficiency of the engine without compromising its performance. According to Cotteleer and Joyce (2014), remaining technique of improving engine performance can include the provision of special coatings in manufacturing the aircraft engine elements. It will help the engine in preventing the environmental attack. Increase in operational life of the aircraft engine helps in increasing the efficiency indirectly. It also helps in commercialization.

Analysis: In the qualitative analysis of the engine materials used in the advanced aircraft engines, engine performance has been increased up to the desired level in last few years. Use of light weight materials in producing aircraft engine has reduced the weight of the aircraft. Hence the thrust needed for takeoff has been reduced. It results in consumption of lesser amount of fuel for same flying circumstances. In case of preventing environmental attack, high strength materials are used for preparing to coat on the upper and lower surface of the airfoil. In case of blade formation in compressor, and turbine, the most important factor is thermal stress resistance, thermal capacity and thermal conductivity of the blade material. According to the design requirement, suitable alloy material is used by the method of optimization to improve the overall efficiency of the engine.

4.4 Summary

This chapter of the dissertation regarding the development of most advanced aircraft engines provides quantitative and qualitative analysis. Critical analysis is done regarding the performance criteria of the aircraft engines. Quantitative analysis is done based on the engine performance of gas turbine engine, geared fan engine, open rotor engine, ADVENT engine and the Leap engine. Other than performance characteristics, dimensional specifications are also analysed in terms of the comparison. Dimensional comparison is done regarding three proposed type of Leap engine. In the qualitative analysis, material requirements are discussed in brief with the techniques of improving the efficiency and durability of the aircraft engine.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

At the end of this dissertation, it can be concluded that several research works are under processing by different aircraft engineers in order to increase the efficiency of the traditional aircraft engine. In this chapter of this research dissertation, recommendations are provided in order to suggest some techniques in the research works for obtaining sustainable development. Due to lack of commercialization, air ticket price is becoming beyond the reach of the common people.

Improvement of efficiency and durability of the aircraft engine will help in reducing the ticket price. Improvement of efficiency also helps in reducing the exhaust emission of the engine by obtaining full utilization of the fuel consumed by the engine. Hence, harmful effect of aircraft emissions on the environment is also an important concern for this research work. The limitations and obstacles faced during conduction of the research work are also coined in the last portion of this chapter along with a implication of future scope.

5.2 Recommendation

Recommendation 1: larger prototype testing for obtaining more practical performance parameters of the next generation engines

Specific	Experimenting with larger prototypes of engine will help in acquiring more practical and accurate experimental data regarding engine performance than that of the small prototypes.
Measurable	Dimensional characteristics of the engines are measured by different dimension measuring tools like screw gauge, side calipers and other inner or outer measurement tools.
Attainable	In case of larger prototypes, more practical situation is created to obtain more practical results from the output of the experiments. This is a costly but still attainable process.

Realistic	Through this kind of research experiment, accurate results can be obtained compromised with the requirement of the floor space and cost for the experiments. In order to offer adequate amount of the safety of the flight passengers, this kind of advanced technical way is realistic way.
Timely	It would take about 3 months for creating a large and actual size prototype.

Recommendation 2: Consideration of environmental factors by reducing the engine emission

Specific	Consideration of the environmental factors of reducing the engine emission would be effective in increasing the efficiency of the engine.
Measurable	The rate of emission of the aircraft engine is obtained by using various emission measuring tools that measure the proportion of the Carbon dioxides and Carbon monoxide.
Attainable	This is a cost-effective way of reducing the number of emissions from the aircraft engines with advanced technical interpretation.
Realistic	This is a realistic approach as environmental degradation is a massive topic of concern for the aircraft manufacturing companies.
Timely	It is expected to take about 6 months for proper implementation of this approach in the research and development methods.

5.3 Linking with objectives

Objective 1: To analyse and explain development of new aircraft engine of ADVENT systems, open-rotor, geared fan, LEAP and gas turbine

This objective can be linked with the quantitative data analysis section and literature review section of this dissertation. According to the research requirement of this dissertation, specific sets of data are presented in tabular and graphical forms to produce a critical analysis of the performance characteristics. Five types of advanced aircraft engines are provided with required information of performance and dimensional characteristics. Basic and traditional design of open rotor engine, gas turbine aircraft engine, geared turbofan, ADVENT engine and the Leap engine are provided in the literature review section in order to produce a required platform for the critical analysis. Overall engine efficiency, bypass ratio, pressure ratio, air intake volume, operational trust, take off thrust generation, the rate of fuel consumptions are discussed in details along with their advantages and disadvantages. A comparative analysis is also provided regarding the performance parameters and dimensional parameters of Leap engines. In the comparative study of Leap engines, compactness of the engine design is also discussed.

Objective 2: To consider environmental, technical and commercial aspects in the aircraft engine design

This objective can be linked with the literature review section and the qualitative data analysis section of this research dissertation. In order to commercialize the implementation of the advanced aircraft engines, environmental commercial and technical aspects are to be considered. Environmental degradation is one of the most concerned topics of the aircraft design engineers. Environmental factors are linked with the reduction of engine emission, which in turn is linked with the reduction in fuel consumption rate of the engines. Rate fuel consumption depends upon the thermodynamic and propulsive efficiency of the aircraft engine and the power output from the propeller shaft. Hence it can be stated that all the technical, commercial and environmental aspects are interrelated.

Objective 3: To outline possible recommendations for improvement of the engine efficiencies and reducing engine emissions

This objective can be linked with the recommendation section of this dissertation. Recommendations are provided based on the system requirements of the aircraft engine. For improvement in the methods of the experiments regarding prototype testing are also provided in this section. Reduction of the engine emission will be considered in the environmental factors of the second recommendation. Brief descriptions are provided regarding measurement of emission from the aircraft engine and the attainability of the development process in obtaining sustainability.

5.5 Research limitations

In this section, challenges and obstacles faced during conduction of the research works are briefed. According to the research requirement, some technical experiments would be helpful in enriching the research work by practical experimental results. Due to limitation in budget allocation, experiments cannot be done by the researchers. Data are collected from the chart and specification chart obtained from scientific experiments regarding advanced engine testing. Lack of time is another burden for the research work regarding development of the advanced aircraft engine for obtaining sustainability in the airline industry. Many specification and implementation problems are yet unknown due to lack of commercialization of the mentioned engine models.

5.6 Future scope of this research work

In aircraft engineering, sustainability of the design is the main concern. In this concern, environmental, commercial and technical aspects are also included. This research dissertation provides sufficient amount of background studies and several data sets as the results from the previously done experiments by the aircraft design engineers. Several research works are yet to be done in recent future to obtain sufficient experimental results from the prototype testing of advanced engines. It will help in identifying the exact specification of the engines.

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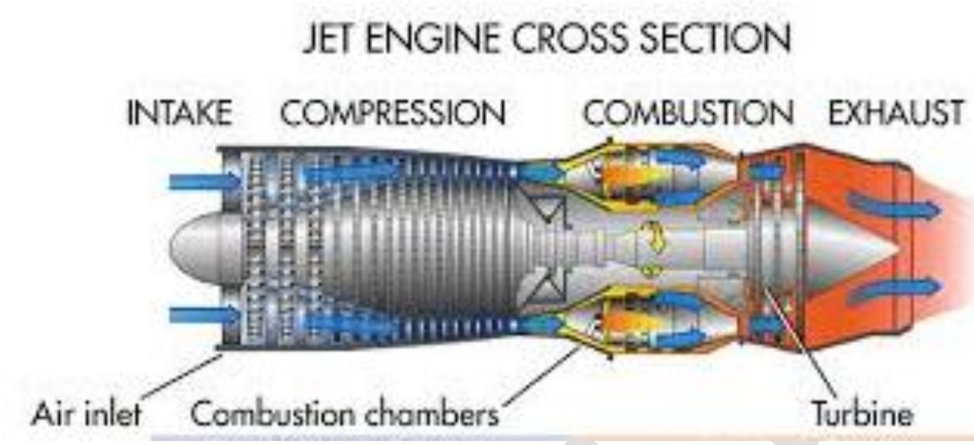
Appendices

Appendix 1: Leap engine

(Source:
https://www.google.co.in/search?Biw=913&bih=606&tbm=isch&sa=1&ei=nzlfwvvsdiml0gsu2iqabw&q=leap+engine&oq=leap+engine&gs_l=psy-ab.3..0l2j0i67k1j0l5j0i30k1j0i5i30k1.86264.91399.0.91705.33.18.0.0.0.0.303.2404.0j1j9j1.12.0....0...1c.1.64.psy-ab..22.10.2231.0..0i24k1j0i10k1.249.qosymjbaedw#imgrc=khmpaolt8qcrom:)

Appendix 2: Gas turbine engine



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Appendix 3: Open and closed rotor engine

(Source:
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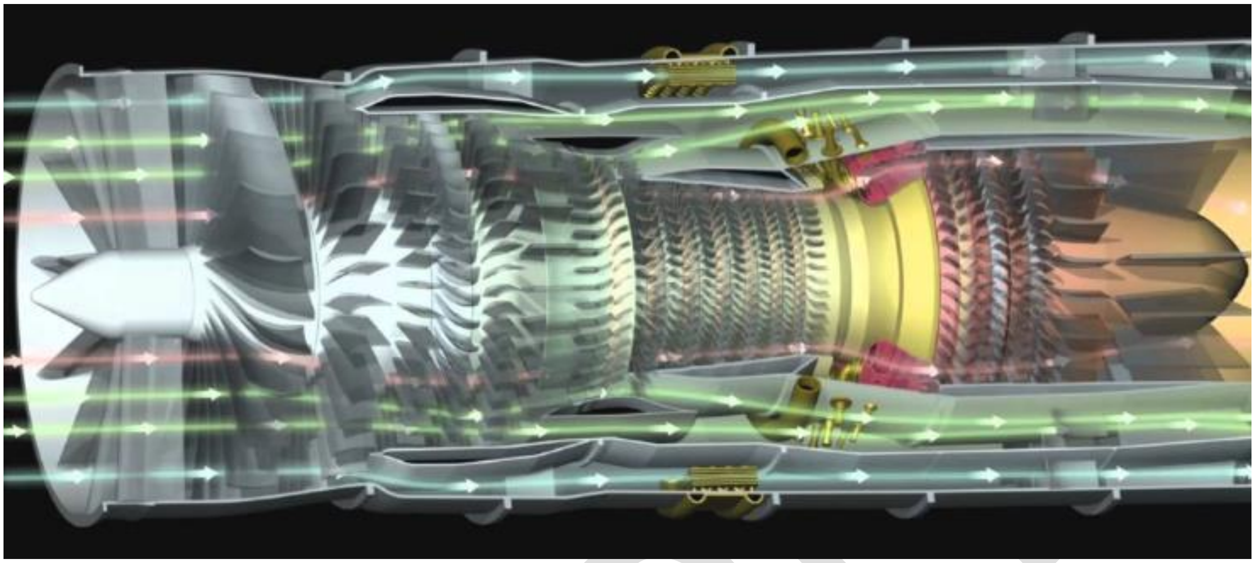
Appendix 4: ADVENT engine



(Source: https://www.google.co.in/search?Q=ADVENT+engine&source=lnms&tbm=isch&sa=X&ved=0ahukewir0i_xio7yahwkzbwkhtsjdeuq_auicigb&biw=1366&bih=662#imgrc=nvxp7d8jzkxq9m:)