EVALUATING THE EFFECT OF DETERIORATION ON THE ENGINE PERFORMANCE AND ITS EMISSIONS RUNNING ON ALTERNATIVE FUELS.

By

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Thesis submitted in fulfillment of the requirements for the Bachelor Degree of Engineering (Honours) (Aerospace Engineering)

JUNE 2018

ENDORSEMENT

I, Senebahven A/L Maniam hereby declare that that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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(Signature of Examiner)

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Date:

DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date:

ACKNOWLEDGEMENT

First of all, I would like to thank my supervisor Dr. Nurul Musfirah Mazlan for her continuous support, valuable advice and guidance throughout the development of this work. She has been of great help to me and her patience towards me has been immense and much appreciated. Without her, this thesis and my ability to complete my Bachelor's degree in time would have not been possible.

I would also like to thank the School of Aerospace Engineering who made it possible for me to pursue this degree in Universiti Sains Malaysia. I would like to also thank all School of Aerospace Engineering administrative staff for their prompt support regarding all administrative matters which enabled me to complete my work on time.

Finally, I would like to convey my sincere gratitude to one and all, who directly or indirectly, have lent their hand in this journey of mine.

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ABSTRACT

The need and the ability to obtain fast as well as reliable global transportation are increasing from time to time. This has set new ground-breaking standards in the aviation industry while creating new challenges along the way in the field of science and technology. As a result of this, the consequences on climate change and on the environment are of huge concern and must be addressed at all levels in the aviation industry. In addition to this, the presence of deterioration will significantly affect the environment and the aviation industry. Hence, these would serve as the purpose of the research work that is being conducted. The research would compromise on investigations with regards to the effect of deterioration on the engine performance and its emission for a complete flight trajectory. The performance of bio-jet fuels on a deteriorated engine for a complete flight trajectory and the emissions emitted will also be investigated in this research. In order to be able to provide significant results, a commercially available test subject is researched. Hence, the CFM56-3 turbofan engine is chosen. The CFM56-3 is a two-spool high bypass ratio turbofan engine. It is commercially known since it is widely used on the Airbus A320 family as well as on the Boeing 737. The existence of previous flight models and data were used to validate the present research model. Jatropha Bio-synthetic Paraffinic Kerosene (JSPK), Camelina Bio-synthetic Paraffinic Kerosene (CSPK) and their blends with Jet-A are bio-jet fuels chosen as part of this research study. The deterioration rate is applied to all components within the CFM56-3 turbofan engine configuration in terms of delta efficiency. The magnitude of deterioration rate was done based on the data obtained from literature review. The parameters that are studied include the effect of the fuels on Thrust Specific Fuel Consumption (TSFC), Thrust as well as Turbine entry Temperature (TET). In terms of emissions, the emissions that will be studied in this study include Nitrogen Oxide (NO_X) and Carbon Monoxide (CO_X).

MENILAI KESAN KEMEROSOTAN TERHADAP PRESTASI ENJIN YANG MENGGUNAKAN BAHAN BAKAR ALTERNATIF SERTA GAS YANG DIHASILKAN.

ABSTRAK

Keperluan dan kemampuan untuk memperoleh pengangkutan global yang pantas serta boleh dipercayai kian meningkat dari masa ke masa. Perkara ini telah menetapkan tahap baru dalam industri penerbangan sambil mencipta cabaran-cabaran yang baru dalam bidang sains dan teknologi. Oleh itu, kesan terhadap perubahan cuaca serta alam sekitar merupakan salah satu perkara yang amat membimbangkan dan harus diberi perhatian pada setiap peringkat dalam industri penerbangan.Seterusnya, kewujudan sifat kemerosotan akan mempunyai kesan yang ketara terhadap alam sekitar dan industri penerbangan. Justeru, hal ini merupakan tujuan utama kajian ini diadakan. Kajian ini merangkumi siasatan berkenaan kesan sifat kemerosotan terhadap prestasi enjin dan gas discajnya untuk satu trajektori penerbangan yang lengkap. Prestasi bahan bakar bio-jet dalam enjin yang sedang merosot serta gas yang discajnya untuk satu trajektori penerbangan yang lengkap juga akan disiasat dalam kajian ini. Enjin berkipas turbo CFM56-3 dipilih sebagai bahan kajian untuk mendapat keputusan yang lebih bermakna. CFM56-3 adalah enjin berkipas turbo yang mempunyai nisbah pintas udara yang tinggi dan digunakan secara komersial dalam keluarga Airbus A320 serta Boeing 737. Kewujudan model serta data yang lama digunakan untuk mengesahkan model kajian yang sekian ada. Jatropha Bio-synthetic Paraffinic Kerosene (JSPK) dan Camelina Bio-synthetic Paraffinic Kerosene (CSPK) serta campuran mereka dengan Jet-A merupakan bahan bakar bio-jet yang telah dipilih untuk kajian ini. Kadar kemerosotan akan diterapkan pada setiap komponen yang terdapat dalam konfigurasi enjin berkipas turbo CFM56-3. Kadar kemerosotan akan diterapkan berdasarkan perbezaan efisiensi. Magnitud kadar kemorosotan adalah berdasarkan nilai yang diperolehi daripada kajian literature. Parameter-parameter yang dikaji dalam penyelidikan ini merangkumi kesan bahan bakar terhadap hasil tujahan, jumlah penggunaan bahan api serta suhu turbin. Gas discaj yang akan disiasat dalam kajian ini merangkumi nitrogen oksida (NO_X) dan Karbon Monoxida (CO_X).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

BLISK	Blade Integrated Disk
BPR	Bypass Ratio
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CR	Compression Ratio
CSPK	Camelina Bio-synthetic Paraffinic Kerosine
JSPK	Jatropha Bio-synthetic Paraffinic Kerosine
LHV	Low Heating Value
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ICAO	International Civil Aviation Organization
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
NOx	Nitrogen Oxide
OPR	Overall Pressure Ratio
SPK	Synthetic Paraffinic Kerosene
TET	Turbine Entry Temperature
TSFC	Thrust Specific Fuel Consumption

LIST OF SYMBOLS

$\dot{m}_0$: Mass Flow Rate [kg/s]

$\dot{m}_a$: Air Mass Flow Rate [kg/s]

$\dot{m}_c$: Core Mass Flow Rate [kg/s]

$\dot{m}_f$: Fan Mass Flow Rate [kg/s]

$\dot{m}_{ff}$: Fuel Flow Rate [kg/s]

C_P : Heat Capacity [kJ/kgK]

f : Fuel to Air Ratio

F : Thrust [kN]

P_0 : Ambient Pressure [bar]

P_2 : Fan Inlet Pressure [bar]

P_3 : Compressor Inlet Pressure [bar]

Q_{in} : Heat Added [J/kg]

Q_{Rej} : Heat Rejected [J/kg]

T_0 : Ambient Temperature [K]

T_2 : Fan Inlet Temperature [K]

T_3 : Compressor Inlet Temperature [K]

T_4 : Turbine Entry Temperature [K]

T_5 : Turbine Exit Temperature [K]

T_9 : Exhaust Exit Temperature [K]

W_C : Compressor Work [J/kg]

W_N : Net Work Out [J/kg]

W_T	: Turbine Work [J/kg]
η_{th}	: Thermal Efficiency
FN	: Engine Thrust [kN]
N_H	: High-Pressure Spool Speed [RPM]
N_L	: Low-Pressure Spool Speed [RPM]

CHAPTER 1

INTRODUCTION

This chapter would serve as a foundation and preface to the topics that would be covered in this research. The problem statement which would serve as the inspiration to the initiation and completion of this project will be identified. The primary objectives and scope of this research will be discussed as well.

1.1.BACKGROUND

The aviation industry is a fast-paced industry and has been through quite a number of changes and challenges for the past thirty years and is very much expected to grow significantly in the near future. The advancement in the field of science and technology has showed that current aircrafts are seventy-five percent quieter and eighty percent more energy efficient. However, with all these advancements, the aviation industry has been identified to contribute approximately two-percent of the global anthropogenic CO_2 emissions with the international aviation contributing sixty-percent of those emissions. Hence, as of the 37th session of the International Civil Aviation Organization (ICAO) assembly, the members have globally decided to improve on fuel efficiency by two percent annually and limit CO_2 emissions at 2020 levels. The strategies that are being considered include alternative fuels, market-based measures, operational changes as well as technological advancements (ICAO, 2013).

The use of alternative fuels as means to improve fuel efficiency and reduce greenhouse gas emissions is a very much dependable method of solution as it provides numerous benefits such as the stabilization of fuel prices, alleviation of petroleum dependence as well as the reduction in greenhouse gas emissions (IATA, 2015). The U.S. Department of Defense (DOD) has set goals to test and certify all aircrafts and systems on a 50:50 alternative fuel blend by 2012, and to ensure that 50% of the domestic aviation fuel of the Air Force comes from an alternative fuel blend by 2025 (Blakeley, 2013). Currently, the alternative jet fuel production is broken down into four categories based on its feedstock and conversion process which are mainly Alcohol to Jet (ATJ), Oil to Jet (OTJ), Gas to Jet (GTJ) and Sugar to Jet (STJ) which can be seen in Table 1.1 (Bauen *et al.*, 2009; Hileman *et al.*, 2009; IATA, 2010; Rye *et al.*, 2010; Agusdinata *et al.*, 2011; Leuphana, 2011; Whitman *et al.*, 2011; Biofuel, 2012; Rosillo *et al*., 2012).

Table 1.1: Alternative Jet Fuel Production Pathways

Category	**Pathways**
Alcohol to Jet (ATJ)	Ethanol to Jet
	Butanol to Jet
Oil to Jet (OTJ)	Hydroprocessed Renewable Jet (HRJ)
	Catalytic Hydrothermolysis (CH)
	Hydrotreated Depolymerized Cellulosic Jet (Pyrolysis or HDCJ)
Gas to Jet (GTJ)	FT Synthesis
	Gas Fermentation
Sugar to Jet (STJ)	Catalytic Upgrading of Sugar to Jet
	Direct Sugar Biological to Hydrocarbons

Despite all of this countless measures and technological advancements, there is one phenomenon that is inevitable in the aviation field which is deterioration. With the available technology today, it is rest assured that the manufacturing of commercially used turbofan engine is at high quality and performance. However, as the flight cycle of an engine increases, deterioration of an engine is most likely to happen and this will have a direct impact on its performance and emission level. The phenomena of deterioration is not only limited to aircraft engines but also occurs in ground vehicles, turbine engines and other machineries as well.

As discussed above, the capability and ability for bio-fuels to reduce emission is very much acknowledged. However, despite multiple computational studies and numerous experimental researches that have been conducted by researchers on bio-fuels, rarely has there been a study on the performance of a deteriorating engine operating under bio-fuels for a complete flight trajectory. A study was conducted by Koh Wei Chong on the performance of a deteriorating engine utilizing bio-fuels (Wei Chong, 2017). Nonetheless, this was conducted at only one operating condition which is at cruise. In R.M.P Gaspar's research, he utilized a wide range of bio-fuels at different operating conditions in which it covered a complete flight trajectory yet it was not performed with a deteriorating engine (Gaspar *et al.*, 2016). Hence, the deterioration effect on an engine performance and its emissions running on alternative fuels for a complete aircraft trajectory would be studied in this research.

1.2.OBJECTIVE

This research was conducted with the fundamental objective to comprehend the performance of turbofan engines and how to enhance them as well as understanding how the utilization of bio-jet fuel will influence the general performance and fuel utilization, intending to help the aviation industry in having less expenditure towards maintenance and fuel. Hence, in order to accomplish these research goals, a model within commercially available simulation software has to be constructed and verified, as well as applying and performing the right conditions and configurations to simulate the research interest situations for the engine. The objectives are as below. It involves the usage of publicly available software and multiple simulations of different settings and operation would be run in it.

1. To evaluate performance and emissions of deteriorated engine running with alternative fuel for all flight phases.
2. To analyze effect of fuel properties on the engine performance and emissions.

1.3.SCOPE

The selected engine that is being discussed and investigated in this research only represents certain configurations and settings whilst the case study is being conducted based on publically available data as well as information reinforced by applicable literature review. Hence, indicating that it may not be feasible. Many external factors are not taken into account due to the presence of limited data. This paper compromises of results that envelope on the effects of a deteriorating engine running on alternative fuels on the engine performance, namely Thrust Specific Fuel Consumption (TSFC), Thrust and Turbine Entry Temperature (TET) as well as on emissions, primarily focusing on Nitrogen oxide and Carbon monoxide.

1.4.OUTLINE

Chapter 1 provides a brief introduction of the research topic and interest. A general statement and discussion with regards to the problem statement will also be presented. The scope as well as the primary objectives of this research will also be presented in this chapter. In addition, the outline of the thesis will also be discussed in this chapter for better understanding.

Chapter 2 would fundamentally include on the literature review of turbofan engines and the analysis of its performance. The chapter would also contain reviews on alternative fuels that have been practiced and analyzed up to date. The chapter would also discuss on the concept of deterioration and its effects on engine performance.

Chapter 3 will primarily discuss on the strategies and methods that were practiced throughout this research project. The software that is being used for the evaluation and analysis of this research would also be introduced. The verification of the test subject will also be presented. Assumptions and considerations that have been introduced in this research will also be discussed in this chapter.

Chapter 4 will discuss on the validation results of the model that is being practiced in this research as well as the findings and outcomes of this research. The results will be presented progressively as per the research objectives. Suitable engine performance parameters would be used to discuss how it is affected at design point and at several off-design cases.

Chapter 5 summarizes the research findings and presents the conclusion on this study. Based on these, recommendations for future work are also discussed.

CHAPTER 2

LITERATURE REVIEW

2.1.Alternative Fuels and its Impact in the Aviation Industry.

The use of air transport has become an inevitable part in this modern world. With that being said, fossil fuels still remain the primary source of energy to date. Global energy consumption increased by one percent in 2014 and 2015 which is much below its ten-year average of 1.9%. In 2015, the energy consumed consisted of f 32.94% petroleum, 29.2% coal, 23.85% natural gas, 4.44% nuclear energy and 9.57% other renewable energy resources (hydro, solar, wind and e.g. (B.D. , 2017; Salvi *et al.*, 2013; Yilmaz *et al.*, 2011).

Due to the production and consumption of energy worldwide, pollutants are released into the atmosphere and most of these pollutants occur due to the presence of fossil fuels (World Energy Council, 2016). Based on the Kyoto protocol, Carbon dioxide (CO_2) emissions play a huge impact on climate change and global warming. An 80% increase in CO_2 emissions from the transportation sector is to be expected by 2030 (OPEC, 2012). The aviation industry is an important part of the transportation sector. As the standards in the modern world increases, the aviation sector has to take a significant role to protect the environment (Yilmaz *et al.*, 2016; Yilmaz *et al.*, 2014; EIA, 2012). The usage of alternative fuels seems to be one of the ways to reduce emission and the consumption of fuels. Alternative fuels have the potential to disrupt the geopolitical balance of power, as well as to affect how businesses and the public consume energy (Chuck *et al.*, 2014).

An ample amount of studies have been conducted in order to acknowledge the suitability and capability of bio-jet fuels in aircraft engines. An experimental study was conducted by Chuck and Donelly to investigate the compatibility of bio-jet fuels as drop-in fuels derived from sustainable sources with Jet-A. Nine fuels were tested in this investigation in which they were tested for energy content, flash point, cloud point and viscosity. The results of the investigation showed that only limonene fulfilled all the requirements of an alternative fuel (Chuck *et al.*, 2014). Rahmes also conducted an investigation to evaluate the effects of Jatropha and Algae-derived Bio-SPK on the performance of engine and emissions. It was tested on a CFM56-7B engine. The first test was conducted using Jet-A followed by 20% and 50% blends of Bio-SPK fuels. The results showed that as the blending percentage of Bio-SPK increased, the heat of combustion increased as well. In contrast, the viscosity and density was noted to decrease as the blend percentage increased. The results also showed that the specific fuel consumption and fuel flow improved as the blending percentage increased (Rahmes *et al.*, 2009).

Mazlan conducted a study where the engine performance specifically thrust, fuel flow and SFC is investigated by understanding the capability of JSPK, CSPK and their blends with Jet-A. The blends were done in the ratio of 50:50. The results showed that blending synthetic paraffinic kerosene (SPK) types of fuels with Jet-A increases the engine thrust. This was due to the high low heating value (LHV) of the blends in comparison to Jet-A. It also showed reduction in fuel flow and improvements in SFC (Mazlan *et al.*, 2015). On the other hand, Mendez et al conducted an experimental study to investigate the effects of butanol/Jet-A blends in a gas turbine engine. The investigation revealed that NO_x and CO emission indices for butanol and butanol blends were lower compared to that of Jet-A. Nonetheless, the operational thrust range of the engine running on butanol based fuels were observed to be reduced as a result of its lower energy content (Mendez *et al.*, 2014).

Dagget conducted a research on different type of potential alternative fuels that are hydrogen fuels, propane or butane, alcohols, bio-jet fuels and synthetic fuels (Dagget *et al.*, 2006). Advantages and disadvantages of each alternative fuels were presented in their study. They also showed that higher thermal stability and cleaner burning fuel in the fuel will result in a reduced deposit of fuel system. Beyesdorf also observed a somewhat similar advantage in his study (Beyersdorf *et al.*, 2013). Another study conducted by Mazlan showed that the production of NO_x and the flame temperature of the combustion chamber were related. The results showed that higher NO_x emission is produced as the flame temperature increases. It was also observed that, the flame temperature of bio-fuels is lower compared to Jet-A during the process of combustion. Hence, the emission of NO_x is lowered. This in return induces the increase in CO formation since the low flame temperature causes the oxidation of carbon atom to be incomplete and thus generating a high amount of CO [Mazlan *et al.*, 2016; Mazlan *et al.*, 2011].

Another notable research can be seen in R.M.Gaspar’s research. He showed that, Most of the alternative fuels considered have improved the engine performance when compared with conventional jet fuel burning, with savings in specific fuel consumption up to approximately 4%. He also showed that, emissions of NOx, CO, UHC and soot have been studied and it was concluded that the use of alternative fuels primarily affects the latter pollutant, leading to an almost generalized and substantial reduction of soot emissions. This is fundamentally associated with the lower aromatics content of these fuels, reflected by a higher hydrogen-to-carbon ratio. Concerning NOx and excluding fuels such as ATJ-SKA and CH, reductions in emissions of about 10% were found for neat products with respect to Jet A-1, essentially resulting from differences in stoichiometric flame temperature. The research was conducted at different operating conditions pertaining that to a complete flight trajectory (Gaspar *et al.*, 2016).

2.2.Turbofan Engine

Turbofan aero-engines are designed to work with prominent quality and efficiency under a wide range of operating conditions. It plays a pivotal role in the flight capabilities of modern aircrafts (Li *et al.*, 2018). Turbofan engines are preferred over conventional turbojet engines due to its ability to provide alleviations in terms of fuel burn efficiency and noise level. The ability to provide efficiency of operation up to Mach number 0.85 in terms of flight velocity is also an advantage that turbofan engines have over turboprop engines. With the available technology today, current turbofan engines have approximately a two-spool or a three-spool design ranging from medium to high bypass ratio. A typical turbofan engine consist of a low-pressure compressor (LPC), a high pressure compressor (HPC), a combustor chamber which also known as a burner, a high-pressure turbine(HPT), a low-pressure turbine (LPT) and a convergent core nozzle, through the core of the engine (hot flow). Cold flow (bypass air) also runs through the fan and the convergent fan nozzle. Figure 1 shows a typical turbofan engine and its station numbering in accordance to the Aerospace Recommended Practice 755A (Gaspar *et al.*, 2016).

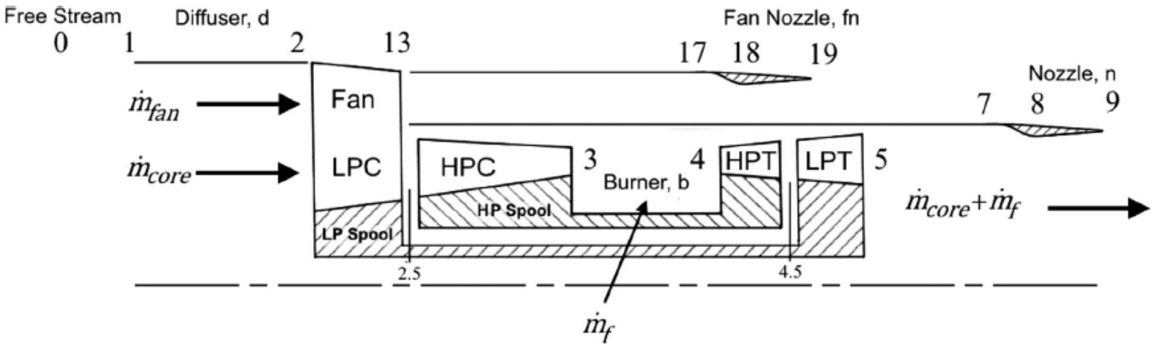

Figure 2.1: A typical turbofan engine schematic configuration (Gaspar *et al.*, 2016)

2.2.1. Turbofan Engine Performance

In order to be able to fulfill a given design requirement or specification, key parameters of engine performance that encloses the overall engine operability and capability should be defined. Two key parameters that define the engine performance of aircraft's gas turbine engines are net thrust (FN) and specific fuel consumption (SFC) (Venediger, 2013). Thermal efficiency, propulsive efficiency and combustion efficiency are factors that affect the value of SFC (Venediger, 2013). For a turbofan engine, the three main parameters that have to be considered are bypass ratio (BPR), the overall pressure ratio (OPR) and the turbine entry temperature (TET). These parameters have an adverse effect on the engine's propulsive and thermal efficiency (Bräunling, 2009).

The engine bypass ratio (BPR) is the ratio between the mass flow rates of air which circumnavigates the core engine to the mass flow rate of air that passes through the core engine which is involved in the combustion process. The increase in the size of the fan diameter has limited the maximum engine bypass ratios in aircraft engines. Another limiting factor is the decrease in the size of the core engine diameter. A large fan diameter would increase the aircrafts total drag as well as the weight of the fan section which compromises of fan blades and the fan hub. Furthermore, an additional Low pressure turbine would be needed to accommodate a larger fan diameter at its desired speed. Apart from that, the compressor stage pressure ratios and the size of the combustion chamber limit the ability to decrease the size of the core engine in order to achieve the desired compressor and combustion efficiencies.

The overall pressure ratio (OPR) is defined as the total pressure at the exit of the compressor in relation to the engine inlet's total pressure. This shows that, the overall pressure ratio depends on the number of compressors in a particular engine configuration. Engine weights and the operating range of the combustor and engine are factors that limit the maximum overall pressure ratio in an aircraft engine. Typical aero-engines have an axially arranged compressor to ensure the optimum delivery of pressure per stage for a given compressor efficiency.

Last but not least, is the turbine entry temperature (TET) in which the mechanical integrity of the combustion chamber and the parts of the turbine which are exposed to the highest gas temperature plays a pivotal role in determining its maximum value. Conventional combustor parts and turbine parts often utilize materials that have an adverse effect on the engine performance. In order to ensure optimum operation of the engine, active cooling of these highly stressed engine parts is extremely significant. Hence, an improved thermal efficiency can be noticed by ensuring a higher turbine entry temperature.

Fletcher and Walsh as well as Braunling have conducted a much more comprehensive study on the correlation between engine’s bypass ratio (BPR), overall pressure ratio (OPR), fan pressure ratio (FPR) and other detailed parametric analyses (Bräunling, 2009; Wörrlein, 2001). Wörrlein specifically addressed in his study regarding the flow characteristics in turbine engine components such as inlets and nozzles as well as their related gas dynamic issues.

2.3.Aircraft Engine Deterioration

The overall performance of an engine very much relies on the interconnectivity of many differently matched component parameters such as combustion temperature, turbine entry temperature, compressor pressure ratios and other parameters as well. Hence, changes in these parameters would have an adverse effect on the overall performance of an engine. It’s an inevitable phenomena that an aircraft engine, a mechanical turbo-machinery would undergo deterioration over its service life (Venediger, 2013). At extended working hours, components will be suffering due to the presence of pollution, erosion, corrosion, wear especially for carrier-based aircraft engine and transatlantic flight aircraft engine. These conditions can cause a little deterioration effect on the engine performance at the early stage of an engine’s life however may cause catastrophic problems such as engine failures if it is prolonged (Lambert, 1991). Thus, it is vital to continuously assess and monitor the condition of an engine from time to time so that a reliable and quality engine can be ensured (Venediger, 2013). A great deal of study on engine performance deterioration has been carried out by NASA. In terms of civil aircraft, the CF6 engine performance was paid great attention in order to determine the cause of its performance deterioration as well as to seek solutions in order to mitigate or eliminate the contributing factors (Wulf, 1980; Sallee, 1980; Diakunchak, 1992).

In industrial gas turbines, deposition was identified to cause 70-85% of overall performance deterioration (Kurz *et al.*, 2012). Large particles that are the main factors of erosion can be removed from the fluid through proper filtration. Nonetheless, the remaining small particle which compromises of the larger fraction that causes deposition remains unresolved (Kurz *et al.*, 2009). The deposition and erosion in aircraft engines are significantly severe in comparison to industrial gas turbines. Hence, the analysis of individual effects still remains as a challenging task.

In industrial gas turbine, the deterioration of engine can be divided into three main categories namely recoverable, non-recoverable and permanent (Kurz et al., 2012). However, aircraft deterioration can be categorized into two categories which are off-wing recoverable performance deterioration, on-wing recoverable performance deterioration as well as permanent deterioration. Off-wing recoverable performance deterioration is defined as deteriorations that can be recovered through off-wing maintenance such as the disassembly and replacement or refurbishment of damaged parts. On-wing recoverable performance deteriorations are deteriorations that can be recovered through on on-wing maintenance such as compressor washing. Last but not least, permanent performance deteriorations are deteriorations that cannot be recovered at an economically justifiable expense. Natural ageing is the main factor of this unavoidable process (Wei Chong, 2017).

2.3.1. Engine Deterioration Mechanism

The major driver for engine performance deterioration in aircraft engine include the degradation of aerodynamic components such as engine compressors, the combustor as well as the turbine in which all of them operate in harsh environments. All of the mentioned degradation modes will have an effect on the parts original geometry, properties and condition (Kurz *et al*, 2007). These deterioration mechanism and their effects is presented and discussed in this chapter.

2.3.2. Corrosion, Abrasion and Erosion

Corrosion distress mainly occurs due to the chemical reaction between the base materials of parts with its environment. Commonly, this phenomenon occurs due to the electrochemical oxidation of the exposed metal part reacting with oxygen from the surrounding air and/or moisture in the air. The cold section engine parts such the steel alloy LPC blades and vanes would be affected due to this type of corrosion. Their integrity would be compromised.

Abrasion occurs as a result of the removal of material due to the rubbing of a moving blade tip against its static lining surface. It also occurs due to the grazing of a rotating inter-stage seal against its stationary counterpart. Flight loads and gyroscopic effects are two contributing factors of these kinds of graze and may cause engine shafts and cases to deflect from their designated location. Thus, decreasing or increasing the blade tip and seal clearances. Additionally, the presence of a high temperature environment may result in the amplification of material contraction which may induce abrasion in engine turbines.

In the context of erosion of part, this particular degradation mechanism is a result of hard particles impinging a surface. This in return causes the reduction of material and diminishment of part’s original thickness. It is a common degradation in airfoils that are in direct contact with the path flow of air. An abrasive effect is only notable when the ingested particle is larger than 10μm in diameter (Sallee, 1980). Common examples of these particles are dust, sand or other floating particles. Other stationary or rotating part can be affected by erosion if it’s exposed to air flow that carries abrasive particles. Cooling air passages and cavities within the engine in which circulation of air is constant, severe erosion might take place.

2.3.3. Thermal Distress

The combustor and turbine are the most common parts that are subjected to very high temperatures either directly by exposition to hot flow path gases or indirectly by their proximity to the engine hot section. Stationary mechanical parts and rotating engine parts are common thermal distress prone areas. These parts may include parts such as combustion chamber liners, turbine vanes, structural turbine cases, frames, turbine disks, turbine blades and rotating seals. Components such as instrumentation devices for engine condition monitoring and fuel nozzles are also affected by thermal distress.

Another identified mechanism which will cause a material loss of the affected component over time due to the chemical reaction between the base material and substances carried in the hot gas is hot corrosion. This type of corrosion is also known as sulphidation and the substance can originate from the fuel or from sources external to the engine such as sulphates or salts. This type of corrosion which is induced by a combination of sodium chloride from the inlet air and sulphur from the fuel may have a detrimental effect on the integrity of hot section engine parts such as high alloy HPT blades and vanes. High temperature oxidation is another known distress mechanism which is induced by a chemical reaction between the base material and free oxygen from the hot gaseous environment. Removal of material from component is inevitable in this reaction. Furthermore, burn-off with significant material detachment due to excessive temperatures can occur in the combustion and turbine section (Sallee, 1980). Immediate failure of the high pressure turbine blades can occur if spalling and removal of the Thermal Barrier Coating (TBC) takes place. This is due to the exposition of the base material to the high, beyond melting point temperatures.

2.3.4. Mechanical Wear

Mechanical wear often takes place in engine oil and oil seals in all parts of the engine. It causes an increase in leakage flow over time. Moving parts such as engine bearings and gearboxes are also prone to mechanical wear and its effects are being researched in the domain of tribology. The presence of rotation and vibration may result in the continuous rubbing of the engine seals against each other during engine operation and in return leading to the removal of base material and consequently an increase in gaps. The effect of abrasive wear may be amplified through the cyclic operation (acceleration and deceleration) of the engine. This may also promote leakages and mechanical wear.

2.4. Turbofan Engine Component Deterioration

The deterioration of components in a turbofan engine is a combined effect of all the mechanism outlined in the previous section which compromises of thermal distress, mechanical wear, corrosion, abrasion and erosion. The following sub-section will outline the causes of the component degradation and provide a quantitative assessment of the amount of degradation that may have been experienced. The representative degradation values were based on the JT9D turbofan-engine family as analyzed by Sallee (Diakunchak, 1992; Sallee *et al*., 1986). In the absence of sufficient data for the CFM56 engine, those for the JT9D have been referred as illustration purpose.

2.4.1. Low-Pressure Compressor Performance Deterioration

LPC deteriorations are caused by increases in tip clearances, rising airfoil’s surface roughness and through the blunting of the fan-blade's leading edges. Fan blade's tip clearance increases with engine usage due to blade tip and casing wear. Most casings are equipped with wear strips to allow break in wear and prevent damage to the blades; however, additional blade growth occurs due to flight loads and transient operations producing gap larger than required for steady state operations. In addition, the wear strips experiences erosion and thereby further increase in the clearances. Engine testing established that tip-clearance increases caused a reduction in both compressor flow capacity and in compressor efficiency (Naeem, 1996). This reduces the compressor's surge margin. Surface roughness, caused by the impact of erosive particles, also adversely affects compressor performance. The study showed that a 10 percent increase in airfoil roughness contributed to a one percent loss in compressor efficiency. It was further established that the roughness builds up rapidly (within the first 1000 cycles) and then remains relatively constant. Particulate matter, entrained into the engine, also causes blunting of the leading edges of the compressor blades: the resulting change in airfoil shape leads to a decrease in compressor efficiency (Macdonald, 1993; Little, 1994).

In summary, for the JT9D, compressor deterioration is dictated primarily by tip clearance increases, surface roughening and airfoil contour changes. The combination of these loss mechanisms results in both a decrease in compressor flow capacity and efficiency (Little, 1994).

2.4.2. High-Pressure Compressor Performance Deterioration

This is qualitatively similar to the LPC. Performance loss is associated with changes in tip clearances, rub-strip erosion, blade-length loss and airfoil erosion. The combined effect of these four deteriorations exceeds that for the fan; total flow-capacity and efficiency losses being as high as 10 and 8 percent respectively (Macdonald, 1993; Kellersman *et al*., 2014)

2.4.3. Combustor Performance Deterioration

This may involve (i) choking of the fuel nozzles thereby changing the fuel-spray pattern, and/or (ii) combustor-casing distortion, which may alter the critical dimensions of the combustor. From a performance perspective, the two parameters of interest are the resulting overall pressure-loss and the combustor efficiency (Little, 1994). However, Sallee found that these two parameters remained relatively invariant despite engine usage (Sallee, 1980). Therefore, combustor deterioration does not have a direct impact on overall performance-loss. Nevertheless, these same deteriorations do have indirect effects on turbine performance. If the fuel-nozzle spray pattern changes or the combustor casing is distorted due to flight loads, the temperature profile as seen by the turbine will change (Macdonald, 1993).

In contrast to the conclusion proposed by Sallee, Little (Kellersman *et al*., 2014) showed that the combustor will experience degradation due to the buckling and bum-through of the combustor liners. He based his opinion on assessments of engine combustors that had been subjected to military-fighter operations.

2.4.4. High Pressure Turbine Performance Deterioration

The performance-loss mechanisms which cause the majority of HPT deterioration are (i) blade-tip clearance increases and (ii) vane twisting and bowing. The surface roughness of the blades also adversely affects turbine performance but compared with the other loss mechanisms, its effect is negligible. Increased clearances between the rotor blades and the casing are caused predominately by centrifugal and thermal loads imposed during engine transients and by distortions of the engine casing as a result of changing flight loads (Kellersman *et al*., 2014).

Vane distortion ensues as a result of both aerodynamic loads (arising from gas pressure bending moments, as well as centrifugal untwist and loads) and from stresses due to thermal gradients. As the vanes distort, coolant air is allowed into the main gas-stream and hence resulting in a reduction in the turbine's efficiency (Macdonald, 1993). The magnitude of the resulting leakage can be as great as 2% of the flow, leading consequently to an efficiency drop of up to 1.5% (Kellersman *et al*., 2014). Bowing of the HPT's vanes causes the flow area to increase and hence an increase in the flow capacity (Little, 1994).

The majority of performance loss due to tip clearance increase occurs in the first 500 flight-cycles. Subsequently, the clearances remain relatively invariant with the majority of flow and efficiency deteriorations occurring as a result of blade twist and bowing (Macdonald, 1993).

2.4.5. Low-Pressure Turbine Performance Deterioration

This is caused by clearance changes, twisting and bowing of turbine vanes and the vane's inner diameter soldering. Vane soldering is caused by the misalignment of the vane's inner platform. This misalignment will result in steps in the inner flow-path surface. Hence, causing aerodynamic losses, and hence a loss in turbine efficiency. The airfoil's surface roughness increases with engine usage, but, its effects are minimal compared with the other loss mechanisms (Macdonald, 1993).

Twisting and tilting of the inner platform relative to the fastened-in-place outer platform will result in the leakage of coolant air into the main-stream gas. The result is a reduction in the LPT's efficiency (Little, 2014; Kellersman *et al.*, 2014). As with the HPT, the LPT may suffer from vane bowing, which causes the gas-path flow area to change, so resulting in a decrease in flow capacity (Little, 1994).

2.5.Research on Engine Deterioration

Kellersman et al conducted an investigation to study the comparison between the performances of a jet engine compressor front stage with Blade Integrated Disk (BLISK) geometry during a flight operation interval due to deterioration effects. The arrangement of blades in which each stage cannot be changed during maintenance is known as BLISK. Results from his study showed an increase in the specific fuel consumption (SFC) and exhaust gas temperature (EGT). This was noticed for both on-wing times of a jet engine as well as the maintenance intervals (Kramer *et al*., 1978).

Sallee as well as Kramer and Smith conducted their study on the service data of the Pratt and Whitney JT9D and General Electric's CF-6 turbofan engines. They concluded that one of the contributing factors of performance deterioration of the high-pressure compressor is the surface finish degradation (Sallee, 1980; Tarabrin *et al*, 1998]. Another study that was conducted showed that among compressor components, the rear stages are less affected in comparison to the front stages. The study also found that stators are being more affected due to the deposition of mass on stators being as twice as high as that on rotors.

On the other hand, Igie et al investigated the effect of different levels of aero-engine compressor fouling on engine performance specifically focusing at short and long-haul missions. The results showed an increment of turbine entry temperature (TET) since a constant thrust was required for their clean condition. Take-off and climb recorded the highest TET since the thrust setting at both of this operating condition was set to its maximum (Igie et al., 2015). Jorgenson et al conducted a study to understand the effect on low-pressure compressor and engine performance during an engine roll back due to ice accretion. At high altitude, when the ice water content is high, ice accretion can occur in the fan as well as in the low pressure compression system where typically air static temperature increases. The presence of warm air causes a portion of ice crystals to melt as ice crystals are ingested into the system. Hence, the mixture of ice-water is allowed, thus causing them to stick to the metal surface of the compressor components. As a result of this phenomenon, blockages on stationary components such as stator vanes will lead to performance deterioration of the compressor and consequently reduce engine thrust (Jorgenson et al., 2014).

An analytical study was conducted by Fuelner *et al* by modifying a two-dimensional, linear, compressible state-space analysis. The study included an unsteady pressure fluctuation that was forced into clade passages to account for engine deterioration and transient. The investigation was performed on commercial aircraft engines for both undeteriorated and deteriorated states. The investigation revealed a 5% loss in stall-margin due to deterioration. A loss of 12% for transient stall margin on undeteriorated engine and 7% for deteriorated engine was found. It was concluded that, during acceleration, the operating lines depart from the steady-state level toward the stall line. This will directly cause an instantaneous drop in stall-margin (Fuelner et al., 1994).

CHAPTER 3

METHODOLOGY

This chapter would present a flowchart and a detailed discussion on the methods that were used to conduct this study. The computational software that was used in this research will also be discussed. The validation process and the data used for it will also be presented in this chapter.

3.1. Flowchart of the Research

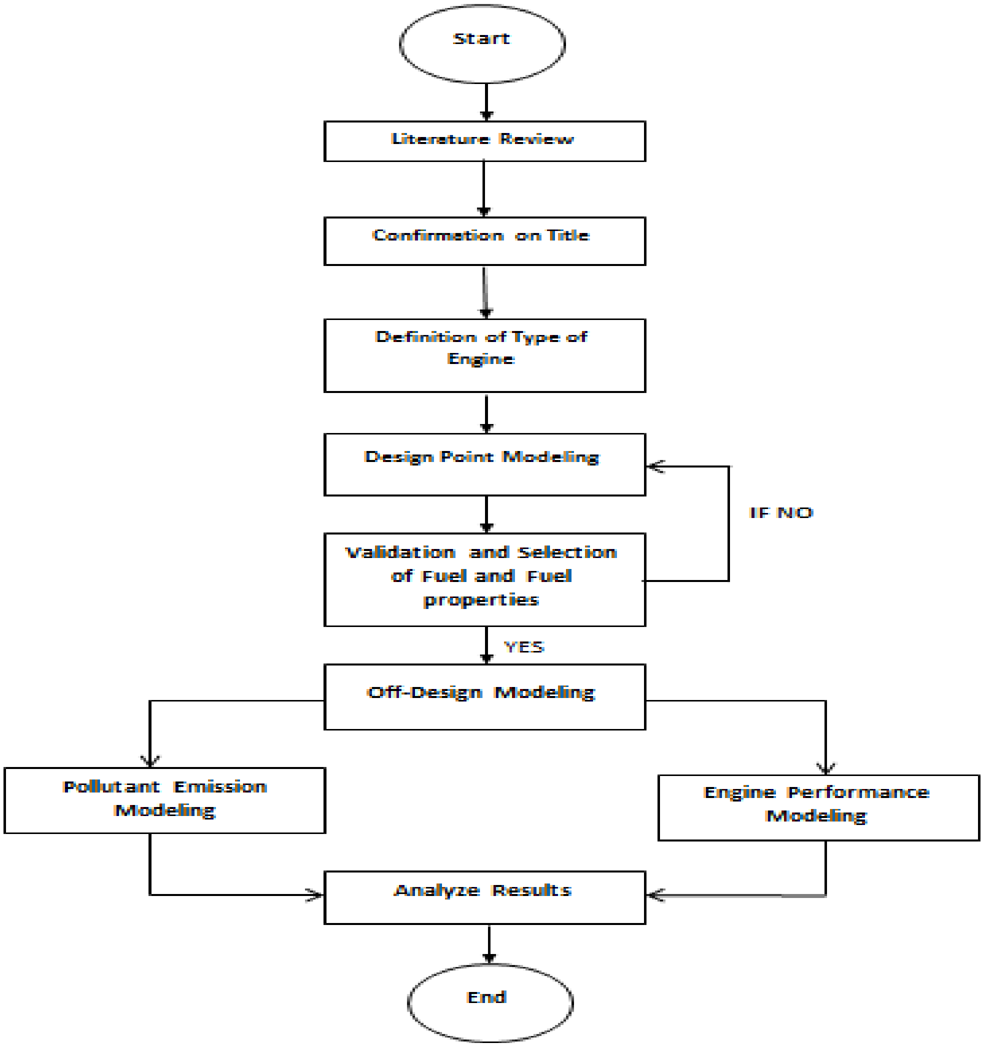

Figure 3.1: Flowchart of the research