A STUDY ON DETERIORATION: THE EFFECT OF ALTITUDE AND BIO-JET FUEL ON TURBOFAN ENGINE PERFORMANCE

by

KOH WEI CHONG

Supervisor: Dr. Nurul Musfirah Mazlan

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ABSTRACT

Air traffic and commercial aviation is very much expected to grow significantly annually in the future and thus it is a concern for all parties that not only the aircraft operation has an effect of the environment, but also the huge amount of investment being placed into aircraft maintenance programs. One important aspect of the aircraft engine is the performance deterioration and this will definitely affect both the environment and the economy. Therefore, these are the main aims of this research work. The first is to study the deterioration effects on aircraft engine performance, followed by the investigation of the effect on operational altitudes on the performance of the deteriorated engine, and lastly the investigation of the performance of bio-jet fuel on deteriorated engine.

The CFM56-3 which is a typical two-spool high bypass ratio turbofan engine, which is widely used on the Boeing 737 and Airbus A320 family, is chosen as the test subject for this study. In addition, existing models and flight data were used for the validation of the present research model. Deterioration rate of the turbofan engine up to 0.1% per day is applied as a deterioration basis for all deterioration studies. Bio-jet fuels such as Jatropha Bio-synthetic Paraffinic

Kerosene (JSPK), Camellina Bio-synthetic Paraffinic Kerosene (CSPK) and their blends with Jet-A were used as the fuel variants for the bio-jet fuel study.

Results obtained on the performance deterioration study with conventional Jet-A fuel shows reduction in air mass flow rate, shaft speed, thrust, thrust specific fuel consumption and exhaust gas temperature with certain deterioration trends within a 30-day period. Also, when the altitudes as ambient conditions were varied, the thrust specific consumptions shows that it is at its lowest when operating at the altitude of 4000m, while thrust and air mass flow rate decreases as altitude increases because of lower air density. In comparison to Jet-A, utilizing bio-jet fuel in the turbofan engine with 0.1% deterioration rate is found to increase engine air mass flow rate, engine thrust and thrust specific fuel consumption due to high value of the fuel’s low heating value (LHV).

Finally, a few additions to the current research framework is discussed in order to increase the simulation quality in the future, as well as to provide a more wide, comprehensive research and understanding on a more realistic representation of the study of gas turbine engine deterioration and the aspects that affect it.

Kajian Mengenai Kemerosotan:

Kesan Ketinggian dan Bahan Api Bio-jet Terhadap

Prestasi Enjin Berkipas Turbo

ABSTRAK

Trafik udara dan penerbangan komersial dijangka meningkat dengan ketara setiap tahun pada masa akan datang dan oleh itu ia adalah satu kebimbangan bagi semua pihak, yang bukan sahaja operasi pesawat akan memberi kesan kepada alam sekitar, tetapi juga jumlah pelaburan yang besar yang diperlukan untuk penyelenggaraan pesawat. Satu aspek penting dalam enjin pesawat adalah kemerosotan prestasi dan ini pasti akan memberi kesan kepada alam sekitar dan ekonomi. Oleh itu, berikut adalah matlamat utama kerja kajian ini. Yang pertama adalah untuk mengkaji kesan kemerosotan prestasi enjin pesawat, diikuti dengan penyiasatan kesan ketinggian pengoperasian enjin terhadap kemerosotan enjin, dan akhir sekali penyiasatan prestasi enjin yang menggunakan bahan api bio-jet.

CFM56-3 adalah enjin berkipas turbo yang mempunyai nisbah pintas udara yang tinggi, yang digunakan secara meluas pada pesawat Boeing 737 dan Airbus A320. Justeru enjin ini telah dipilih sebagai subjek ujian untuk kajian ini. Di samping itu, model sedia ada dan data penerbangan telah digunakan untuk mengesahkan model penyelidikan ini. Dianggarkan enjin berkipas turbo akan mengalami kadar kemerosotan sebanyak 0.1% setiap hari, dan ia akan digunapakai sebagai asas kemerosotan dalam kajian ini. Bahan api bio-jet

seperti Jatropha Bio-synthetic Paraffinic Kerosene (JSPK) dan Camellina Bio-synthetic Paraffinic Kerosene (CSPK) serta campuran mereka dengan Jet-A telah digunakan sebagai varian bahan api untuk mengkaji kesannya terhadap kajian kemerosotan enjin.

Bagi kes bahan api Jet-A, keputusan kajian kemerosotan yang diperolehi menunjukkan pengurangan kadar jisim udara, kelajuan aci, hasil tujahan, jumlah penggunaan bahan api dan suhu gas ekzos dengan trend kemerosotan tertentu dalam tempoh 30 hari. Sebagai tambahan, apabila ketinggian operasi kapal terbang telah diubah, penggunaan bahan api yang paling rendah diperolehi apabila enjin beroperasi pada ketinggian 4000 m, manakala aliran jisim udara dan daya tolakan enjin berkurangan apabila ketinggian bertambah. Ini disebabkan oleh kepadatan udara yang makin rendah s Berbanding dengan bahan api Jet-A, penggunaan bahan api bio-jet dalam enjin berkipas turbo dengan 0.1% kadar kemerosotan telah meningkatkan kadar aliran jisim udara dalam enjin, daya tolakan dan penggunaan bahan api kerana ketinggian nilai pemanasan rendah bahan api (LHV).

Beberapa tambahan kepada rangka kerja penyelidikan sedia ada turut dibincangkan bagi meningkatkan kualiti simulasi. Ia adalah penting dalam menyediakan penyelidikan yang lebih luas, menyeluruh serta meningkatkan pemahaman terhadap kajian kemerosotan enjin yang lebih realistik dari segi aspek-aspek yang mempengaruhinya.

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I also place on record, my sense of gratitude to one and all, who directly or indirectly, have lent their hand in this journey.

DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

KOH WEI CHONG

Date:

STATEMENT 1

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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STATEMENT 2

I hereby give consent for my thesis, if accepted, to be available for photocopying and for interlibrary loan, and for the title and summary to be made available to outside organizations.

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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
EGTM	Exhaust Gas Temperature Margin
EHM	Engine Health Monitoring
FOD	Foreign Object Damage
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ICAO	International Civil Aviation Organization
JSPK	Jatropha Bio-synthetic Paraffinic Kerosine
kg	kilogram
LCF	Low Cycle Fatigue
LHV	Low Heating Value
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
MJ	Mega Joule
NDT	Non-Destructive Testing
NOx	Nitrogen Oxide
OAT	Outside Air Temperature
OPR	Overall Pressure Ratio
RPM	Revolutions Per Minute
s	second
SPK	Synthetic Paraffinic Kerosene

NOMENCLATURE

Symbol	**Definition**	**Unit**
$\dot{m}_0$	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	
EGT	Exhaust Gas Temperature	K

FN	Engine Trust	kN
N1	Shaft Speed 1	RPM
N2	Shaft Speed 2	RPM
SFC	Specific Fuel Consumption	Kg/MJ
TET	Turbine Entry Temperature	K
TSFC	Thrust Specific Fuel Consumption	kg/kNs
W1	Air Mass Flow Rate	kg/s
Wf	Fuel Flow Rate	kg/s

Subscripts

Symbol	**Definition**
C	Compressor
c	core
f	Fan
ff	fuel
T	Turbine

1.0 INTRODUCTION

This chapter offers a general introduction to the topics of this research interests. Problem statement as the motivation for the commencement of this research project will be identified. Main objectives and scope of this research project also will be discussed.

1.1 Background

Commercial aviation is expected to grow significantly in the future. Demand in reliable and fast global transportation is increasing and has already set countless new standards for the aviation industry, at the same time, creating new possibilities and challenges in the field of science and technology. With the level of technology advancements today, the manufacturing of turbofan engines are usually of high quality and performance. However, once an engine is no longer a clean engine, deterioration of its performances occur. When that occurs, a major concern is that the level of emission and consequences for climate change problem has to be addressed. Deterioration will reduce engine components' efficiency, requires more fuel to be burnt hence increases engine emissions level.

The phenomenon of deterioration is inevitable since every used engine, whether on motorcars, or any machinery or forms of transportations, will deteriorate over time. For aero gas turbines, the main mechanisms of deterioration are contributions of mechanical wear, thermal distress as well as abrasion, corrosion and erosion[1]. For example, in aircrafts, deterioration will effect upon many aircraft operational parameters, which will impede the operations of aircrafts. In most cases, if the deterioration is beyond allowable limitations, it will cause losses in terms of performance and economy to airline operators. Hence, in general, deterioration will cause more expenditure and is harmful to the environment.

Global air traffic has doubled in size once every 15 years since 1977 and according to the Airbus Global Market Forecast 2013-2032[2], it will continue to do so. With the crowded airspace and the increasing number of airline operators, emission from fuel gas turbine engines has been a highly debated issue. This leads to some aviation regulatory boards and airline operators implementing the use of bio-jet fuel mixture in their aircraft engines, which will reduce emission, at the cost of performance cutback. In addition, it also can be used in an engine without any significant engine modification. Studies have been performed to investigate the capability of bio-jet fuels as drop-in fuel in aircraft engine. Chuck and Donnelly [3] performed experimental study to investigate the compatibility of nine different potential bio-jet fuels derived from sustainable sources with Jet-A. The fuels were tested for viscosity, cloud point, flash point, and energy content. From their observation only limonene is found to fulfill all requirements of an alternative aviation fuel. Mendez et al [4] investigated the effect of butanol/Jet-A blends in gas turbine engine. Butanol is an alcoholic type of fuel which has properties that much closer to petroleum fuels such as gasoline/Jet-A. Results obtained showed that NOx and CO emission indices were lower for butanol and butanol blends compared to Jet-A. However reduction in operational thrust range of the engine for butanol-containing fuels was reduced due to its lower energy content. In other study conducted by Mazlan et al [5] have found that blending synthetic paraffinic kerosene (SPK) types of fuels with Jet-A increases engine thrust due to higher value of the fuel’s low heating value (LHV) compared to Jet-A.

High energy content in SPK also is found to contribute on the reduction of flame temperature hence reducing NOx emission although increases in CO production was observed [6]. The production of CO associates with an incomplete combustion. Incomplete combustion may have been affected by low flame temperature because colder temperature will lead to incomplete oxidation of the carbon atom [7].

Based on the above studies, the capability of bio-jet fuels in reducing engine emissions is assented. Although many numerical analysis and experimental works have been done by many researches to identified the capability of bio-jet fuels, rarely have been studied the performance of deteriorating engine utilized with bio-jet fuels. As mentioned above, aircraft engine components will deteriorate over times. This is equally important to understand the performance of bio-jet fuels in utilizing engine requirements. Furthermore to the best of the author’s knowledge, this study in the first to analyze the performance of bio-jet fuels on the deteriorated engine.

1.2 Objectives

This research was carried out with the main objectives to understand the performance of gas turbines and how to improve them as well as understanding how the usage of bio-jet fuel will affect the overall performance and fuel consumption, aiming at helping aircraft operators saving expenditure on maintenance and fuel. To achieve the research objectives, a model within a 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 specific objectives are as follows, which all involves running simulations within a simulation software which is publicly available.

1. To investigate deterioration effects on engine performance.
2. To investigate the effect of operational altitudes on the performance of deteriorated engine.
3. To investigate the performance of bio-jet fuel on deteriorated engine.

1.3 Scope

The particular engines used for investigation in this study only represents certain configurations and case study based on the publicly available data and assumptions supported by the applicable literature review and thus may not necessarily be feasible. With limited data available, many external factors and operational aspects such as the regulations restriction and typical airport procedure are not taken into account.

1.4 Outline

The thesis is divided into five main chapters with each chapter being divided or subdivided into further sections and subsections.

Chapter 1 provides a general introduction to the research interests. A brief discussion on problem statement will be presented. The main objectives and scope of work in conducting this study is discussed. Additionally thesis outline is presented in this chapter.

Chapter 2 will provide a comprehensive literature review on basic gas turbine engine technologies and their implications on performance analysis. It also provides a review on bio-jet fuels used in the aviation industry to date.

Discussion on the concept of gas turbine engine deterioration and its effect on engine components and performance will be included.

Chapter 3 will explain on the methods in which the whole research project has been conducted. Some assumptions, considerations, analysis and statements with regards to the basic gas turbine engine performance deterioration is introduced. Furthermore, the software used for the evaluation as well as the verification of the test subject will be presented.

Chapter 4 will present the results of the model verification process as well as the findings of the whole research. The results will be discussed in chronological order of the research objectives. Also, in an analytical perspective, the findings will also be discussed based on suitable engine performance parameters and how it will affect the gas turbine engine itself at the design point and 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. Lastly, future developments in gas turbine engine performance prediction concludes this study.

2.0 LITERATURE REVIEW

2.1 Aero-engine Technology

Most of the major propulsion systems for civil aircraft in service today are using gas turbine engines, with turbofan engines being the most widely used engine variant for short-to-medium and long range applications. One of the greatest advantage of this engine type is that turbofan engines offers relatively good fuel efficiency and low noise levels comparing to conventional turbojet engines[1]. In terms of flight velocity, turbofan engines has an efficient operation Mach number up to 0.85, which is an advantage compared to a turboprop engine[8]. Turbofan engines also has a medium to high bypass ratio direct drive turbofan engine, usually with two or three spool designs. These engines covers a conventional configuration with a large single-stage fan, a multi-stage low pressure compressor, a multi-stage high pressure compressor, an annular combustor, a multi-stage high pressure turbine and a multi-stage low pressure turbine as shown in Figure 1.

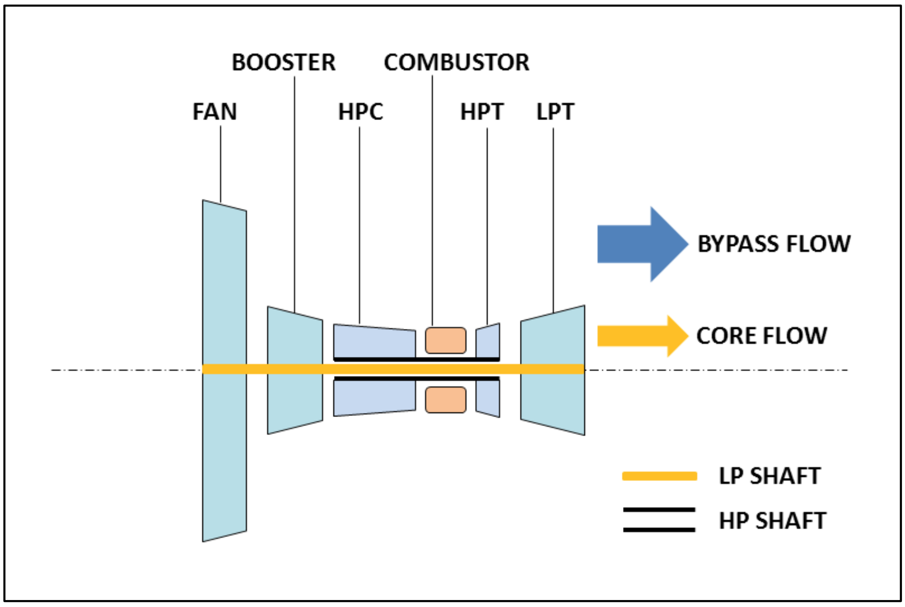

Figure 1: Typical two-shaft turbofan engine configuration[1]

2.2 Turbofan Engine Performance

There are key parameters that define the engine's performance to meet a given design specification. The two major key parameters which describe the engine performance for an aircraft gas turbine engine is the net thrust (FN) and the specific fuel consumption (SFC) or sometimes thrust specific fuel consumption (TSFC). SFC is usually influenced by factors such as thermal efficiency, propulsive efficiency and combustion efficiency[9]. There are also three main design parameters of a turbofan engine. They are the turbine entry temperature (TET), overall pressure ratio (OPR) and bypass ratio (BPR). A change in these three parameters will significantly affect the engine thermal and propulsive performance.

The maximum TET in an aero engine combustors is usually limited by the mechanical integrity of the combustion chamber and the turbine parts which are exposed to the highest gas temperatures in the whole engine. Apart from the materials available used for manufacturing, these highly thermal stressed engine parts can be applied with active cooling to ensure efficient operation. Hence, an engine which allows higher TET will normally yield greater thermal performance[10].

The overall pressure ratio (OPR) represents the relationship of the total pressure at the compressor exit and the total pressure at the engine inlet. This heavily depends on the number of compressors and the individual compressor design ie: the number of stages. Maximum overall pressure ratios in aero engines are usually limited by the maximum permissible engine weight and the operation ranges of the combustor and the turbines.

The engine bypass ratio (BPR) is the ratio between air mass flow rate of air which bypasses the core of the engine to the air mass flow rate passing through the core engine. The air which passes through the core will be involved in the combustion process. Maximum engine bypass ratio is aero engines are usually limited by the size of the fan diameter or by the decrease in size of the core engine diameter. Extremely large fan will increase the aircraft total drag disproportionally as well as the weight of the fan section. Also, a larger fan requires a higher shaft speed. On the other hand, decreasing the size of the core engine is limited by compressor stages pressure ratio and the size of the combustion chamber.

More detailed elaboration of the correlations between engine overall pressure ratio (OPR), bypass ratio (BPR) and the fan pressure ratio (FPR) with detailed analyses and diagrams can be found in the works of Walsh, P.P. and P. Fletcher[9] and in the work of Bräunling, W.J[10].

2.3 Gas Turbine Engine Deterioration

As mentioned in the previous section, overall engine performance relies heavily on many matched components such as turbine entry temperature (TET) and compressor pressure ratios. For a mechanical turbomachinery such as a gas turbine engine, substantial wear and tear over its service life is inevitable. Gas turbines are subject to gradual deterioration of engine performance with increasing time of operation [11] In industrial gas turbines 70 – 85% of overall performance deterioration is estimated which causing by deposition [12]. Large particles causing the erosion can be removed from the fluid through proper filtration. However the remaining large fraction of small particles that causing deposition is difficult to be removed [13]. Unlike industrial gas turbines, deposition and erosion in aircraft engine superimpose each other. This making quantification of the individual effects from in-service data a challenging task. Sallee [14] and Kramer and Smith [15] evaluated in-service data of the Pratt & Whitney JT9D and General Electrics CF-6 turbofan engines and found that one of the main factors causing performance deterioration of high-pressure compressor is surface finish degradation. It is found that among compressor components, front stages being more affected than rear stages, and stators being more affected that rotors with the deposition of mass on stators was approximately twice as high as that on rotor [16]. Rapid roughness was estimated to build up within the first 1000 flight cycles and remain approximately constant afterward. Severe performance deterioration due to both erosion and deposition was reported by aircraft engine operators [14, 15, 17, 18].

Therefore it is essential to monitor and assess the condition of the engine continuously in a continuous airworthiness program to ensure reliable and safe gas turbine operation. In industrial gas turbine, deterioration can be classified into three categories: recoverable, non-recoverable and permanent [12]. However in aircraft, deterioration can be categorized as (1) On-wing recoverable performance deterioration which can be recovered by on-wing maintenance such as compressor washing. The occurrence of a single or multiple random events such as material failures, foreign object damage (FOD) require operational procedures taken during take-off derate, engine operational habits and airport regulations as well as maintenance procedures to preserve the engine condition [1], (2) Off-wing recoverable performance deterioration which can be recovered by off-wing maintenance such as disassembly and replacing or refurbish the damaged parts, and finally (3) Permanent performance deterioration which cannot be recovered at economically justifiable expenses. This is usually happen due to natural ageing which constitutes to an unavoidable process.

Engine degradation monitoring or Engine Health Monitoring (EHM) is an essential instrument for gas turbine operation and is necessary to determine engine performance and also to allow a prognosis for future performance trends prediction and estimation[19]. Typically, the minimum data that is recorded for performance analysis consists of pressure and temperatures of the engine gas path as well as shaft rotational speed and fuel flow. In addition to those parameters, vibration data, engine oil temperature and pressure is also used for analysis. Apart from obtaining the parameters through sensors, visual inspection is also done either using direct visual such as the borescope or indirect visual methods such as non-destructive testing (NDT)[20].

One common measure primarily used to determine actual engine condition in terms of operational performance is the measurement of the engine exhaust gas temperature (EGT), which in turn allows the calculation of exhaust gas temperature margin (EGTM). This method is used by many major airline operators and has proven to give reliable results on the engine health. It is usually measured at locations after the high pressure turbine exit or at the first stages of the low pressure turbine.

2.3.1 Typical Mechanisms of Engine Deterioration

The two main categories of engine degradation described in the previous section are initiated by the alteration of several mechanical and/or chemical properties of the gas turbine engine parts. The degradation of aerodynamic components, such as the engine compressor, the combustor, and the turbine which all operate in harsh environments, is a major driver for engine performance deterioration. This is because all of the below mentioned degradation modes will cause a change of the parts original shape, properties and condition[21]. A general overview of these deterioration mechanisms and their effects are presented in this chapter.

2.3.2 Mechanical Wear

Engine air and oil seals in all parts of the engine are most easily affected by mechanical wear which causes an increase in leakage flow over time. But also engine bearings, gearboxes and other moving parts are subject to mechanical wear and many of the resulting effects are being researched in the domain of tribology. Continuous rubbing of the engine seals against each other during engine operation due to rotation or vibration leads to base material removal and consequently an increase in gaps. Cyclic operation (acceleration and deceleration) of the engine amplifies this abrasive wear effect and promotes leakages and mechanical wear.

2.3.4 Thermal Distress

The main parts that are subjected to very high temperature in a gas turbine engine either directly or indirectly are the combustor and turbine parts. This also includes stationary mechanical parts such as combustion chamber liners, turbine cases, frames and vanes as well as rotation parts such as turbine disks, blades and rotating seals. Instrumentation devices and the fuel nozzles used for engine monitoring are also affected by thermal distress.

With thermal distress, one common mechanism of deterioration is hot corrosion, which is the loss of material. This is caused by the chemical reaction between the base material and substances carried in the hot gas. Another known distress mechanism is high temperature oxidation which is caused by the chemical reaction between free oxygen from the hot gaseous environment and the base material. Similar to hot corrosion, this will lead to loss of materials in engine parts[22].

2.3.5 Abrasion, Corrosion and Erosion

Abrasion is defined as material removal due to rubbing. One example is the rubbing of moving blade tip against its stationary lining surface or due to the rubbing of rotating interstage seal against its stationary counterpart. Flight loads and gyroscopic effects causes the rubbing which in turn caused the engine shafts and cases to deflect from their initial positions. This can increase or decrease blade tip seal clearance, both of which is a defect.

Corrosion distress usually happens on parts by chemical reaction of the base material with the environment. Most of the corrosion cases happen where exposed metal parts react with the surrounding air or air with moisture. Cold section engine parts such as alloy LPC blades can lose the structural integrity with this type of corrosion.

Erosion is usually caused by hard particles impinging a surface, thus rubbing away or replacing material and diminishing the parts' initial thickness. Airfoils are where erosion common occur as they are the parts which are in direct contact with the flow-path air. Common hard particles includes dust, sand and other floating particles. Abrasive particles can also erode the stationary parts within the flow-path air[22].

2.4 Effects of Engine Deterioration

This chapter focuses on the effects of the previously described engine deterioration mechanisms. The first subsection will address the impact of deterioration on engine performance and the second subsection will discuss the effects of deterioration on engine life.

One degraded engine which has operated for a substantial amount of time in service will show a higher fuel consumption compared to the initial fuel consumption values right at the test bed right after production. This means that the engine SFC will increase overtime due to the deterioration of the engine component efficiencies, mainly the compressor, the combustor and the turbines[1].

As mentioned in previous sections, a commonly used parameter to describe the current engine condition is the exhaust gas turbine margin (EGTM). This value is calculated by subtracting the maximum allowable EGT provided by the engine manufacturer from the actual EGT measured during engine operation. The maximum allowable EGT (EGT redline) represents the limit established by the engine manufacturer during certification tests and marks the maximum acceptable temperature at which the engine can operate without suffering rapid deterioration. Peak EGT values are usually reached at or shortly after take-off and thus depend on the OAT (Outside Air Temperature). The effect on the EGT margin for a clean and deteriorated engine is shown in Figure 2. In short, the deteriorated engine will have a lower EGT margin than the clean engine and thus operates with decreased performance margins.

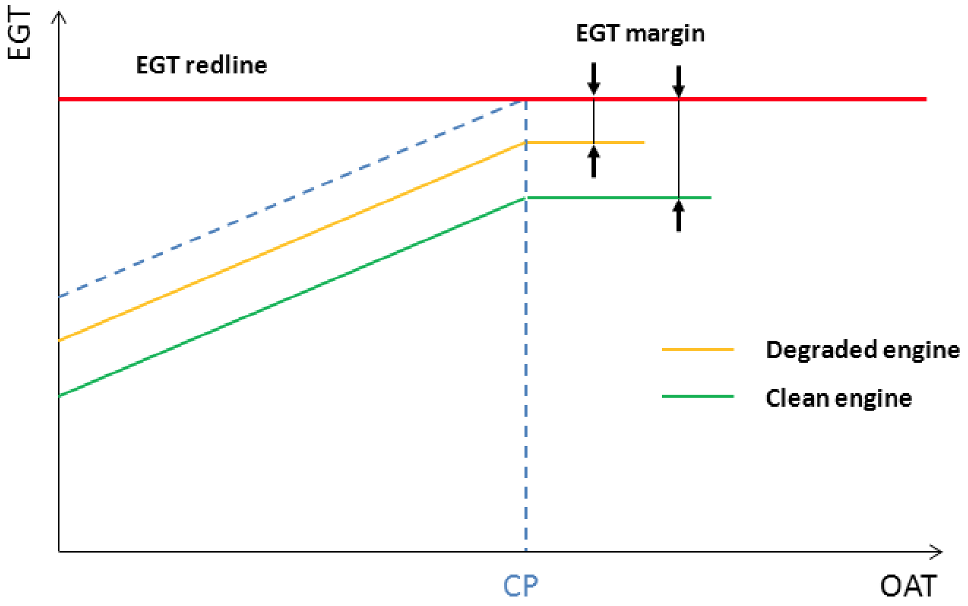

Figure 2: Comparison between EGTM of clean and degraded engine[1]

2.4.1 Effects of Engine Deterioration on Engine Performance

There are two important factors which determine the engine performance and which have an effect on the engine condition. The first factor is the engine operational design scope with regards to maximum take-off thrust levels at a maximum ambient temperature representing the how hard the engine is pushed towards its limitations. These limitations are directly linked to the maximum achievable combustion temperatures in the combustor, and thus directly linked to the turbine entry temperature TET. For example, continuous high power take-offs at high ambient temperatures will accelerate the deterioration of the engine.

The second factor is the engine utilization rate in terms of hour to cycle ratio (stage length) and the engine environmental and climatic operational envelope. For example, the cyclic deterioration of the engine will be accelerated with a high daily aircraft utilization in terms of cycles flown. On the other hand, environmental conditions differ depending on the global region and the amount of erosive or anthropogenic pollutants in the air has a substantial effect on engine performance degradation as discussed in previous subsections[23]. With these both factors combined, the overall engine degradation over time will be determined[1].

2.4.2 Effects of Engine Deterioration on Engine Life

The engine life is mostly determined by the engine manufacturers who usually limit the life of certain parts based on their study on the particular engine's thermal behavior, material behavior, loads and stress calculations, testing, safety factor and aviation agencies requirements. However, the predetermined life limits of the engine parts may change throughout the course of the engine model lifetime based on the operational experience and habits.

The low-cycle fatigue (LCF) life limitations are mainly determined by the number or cycles which are under high load conditions. The amount of change in the material properties under a peak stress condition will then have an impact on the LCF. LCF will become the limiting factor for the total life of rotating engine parts in short range applications, whereas on longer range applications, the limiter will be the creep life of the parts. The nature of loading, component size, surface finish stress and strain concentrations will also affect the fatigue behavior[24]. These high loading conditions are usually reached during the takeoff where the power settings all can impose the highest stress on almost all engine parts. This is where thrust derate procedure comes in, where the reduction of takeoff thrust can significantly lower the peak stresses, which in turn will positively affect the low-cycle fatigue life.

Other than the thrust reduction, the reduction in peak temperatures in the engine hot section will also improve the LCF life. A lower TET will definitely decrease the amount of thermal fatigue against nearby parts. On the other hand, with the engine deteriorating over time due to normal operations, a higher TET is required to maintain the same takeoff thrust. Thus, the thermal stresses in the hot section will increases, which is unavoidable. This will increase both LCF life and thermal fatigue[25].

2.4.3 Previous study on Engine Deterioration

Unlike industrial stationary gas turbine, the impact of engine component deterioration on civil aero engines application has not been widely investigated or available in open literature. Igie *et al* [26] studied the effect of different level aero-engine compressor fouling on engine performance particularly at short and long-haul missions. Two different aircraft with different two-spool engine were used. They observed increment in turbine entry temperature (TET) for both aircraft engines in order to maintain the same level of thrust as their clean condition. The highest TET is observed during take-off and climb when thrust setting is the highest.

Kellersman *et al* [27] performed numerical study in comparing the performance of a jet engine compressor front stage with Blade Integrated Disk (BLISK) geometry during a flight operation interval due to deterioration effects. BLISK is an arrangement of blades in which each stage cannot be changed during maintenance. Erosion is a significant type of deterioration which will lead to misshaped of the airfoils as well as reduction in chord length and an increase in tip clearance. Another deterioration effect are changes in stagger angle. Unlike conventional compressor front stage, due to restrictions in removing the blade, deterioration effects will grow stronger in BLISK until part reaches its life limit. Results obtained from the numerical study shown increases in specific fuel consumption (SFC) and exhaust gas temperature (EGT), both having an influence on the On-Wing-Time of a jet engine and hence the maintenance intervals. However for the conventional blade rows, the blade can be arranged, so the coupled effects can be minimized and the performance can be restored. For a BLISK, the arrangement cannot be changed leading to mistuned stage hence drop engine performance and efficiency. Jorgenson *et al* [28] utilized a computer tool in understanding the low pressure compressor and engine performance during an engine roll back event caused by ice accretion. Ice accretion can occurs in the fan low pressure compression system when the aircraft operates at high altitude in which ice water content is high. In general, air static temperature typically increases in fan and low pressure compression system. As ice crystals are ingested into the systems, a portion of the ice crystals melt due to the warmer air. This allows the ice-water mixture to stick to the metal surfaces of the compressor components. This will result to the blockage on stationary components such as the stator vanes hence resulted into the deterioration in performance of the compressor and consequently reduces engine thrust.

An experimental and analytical study was performed to investigate the influence of compressor deterioration on engine dynamic behavior and transient stall-margin [29]. The analytical study was performed by modifying a two-dimensional, linear, compressible state-space analysis developed by Fuelner *et al* [30] by including unsteady pressure fluctuation forcing in the clade passages to account for engine transients and deterioration, with the latter modeled as increased tip-clearance and flow blockage. Whilst the experiments were performed on large commercial aircraft engines in both undeteriorated and deteriorated states. Results showed losses in stall-margin of about 5% due to deterioration. Measurement on transient stall margin has yield to 12% losses for undeteriorated engine and 7% for deteriorated engine. This is because during acceleration transients the operating lines depart from the steady-state level toward the stall line, thus reducing instantaneous stall-margin.

2.5 Alternative Fuel in Aircraft Engine

Over the years, the aviation industry has grown rapidly. It can be seen by the impact of the increased number of aircraft to the environmental pollution. Studies has shown the average percentage of pollutants produced from aircraft engines. An aircraft produces the largest amount of CO_2 (49%) followed by NO_x (22%), contrails (20%), soot (5%) and water vapour (4%)[31]. There are many technologies available in terms of helping to reduce the emissions and consumption of fuel, one of them is the usage of alternative fuels.

Although facing with certain challenges, the potential of alternative fuels in reducing gas emissions is promising. Despite that, when comparing alternate fuels to fossil fuels such as Jet-A, the sources of the alternative fuels were claimed to be unsuitable for use as bio-jet fuels, which owes to the negative impact towards the environment and then the economy. Also, the poor properties of alternative fuels will make utilization as a jet fuel difficult, and also not fully attuned to the combustion conditions of a gas turbine engine[31].

Many studies have been performed to identify the capability of bio-jet fuels in aircraft engine. Dagget *et al* [32-34] studied different type of potential alternative fuels namely as hydrogen fuel, other liquefied fuels such as propane or butane, alcohols, bio-jet fuels and synthetic fuels [35]. In their study, advantages and disadvantages of alternative fuels are presented. Cleaner burning fuels with no sulfur and higher thermal stability contain in synthetic fuels will result in less fuel system deposits which is of importance to high performance military aircraft engines. This advantages also can be observed in Beyesdorf *et al* [36]. However poorer lubrication, lower volumetric heat content of the fuel contribute to the fuel system elastomer leakage (lack of aromatics reduces seal well) and increased CO_2 emissions during its manufacture. In addition, poor high thermal stability characteristics of the fuel be a major challenge. However blending the fuel with Jet-A improved thermal stability requirements. Additionally blend fuel also can improved other important parameters such density to ensure the specifications of the current aviation turbine fuel is met [37].

One notable research is conducted by Rahmes *et al* [38]. Who performed an experimental study to evaluate the impacts of Jatropha and Algae-derived Bio-SPK on engine performance and emissions. The test subject was the CFM56-7B engine which was first set to run with Jet-A, followed by 20% and then 50% blend of Bio-SPK fuels. As the blending percentage of Bio-SPK increases, it is noted that the heat of combustion increases as the density and viscosity decreases. Also, the increase in blending percentage of Bio-SPK improved the specific fuel consumption and fuel flow.

In another study conducted by Mazlan *et al* [5, 6, 39], the capability of JSPK, CSPK and their blends with Jet-A on engine performance specifically thrust, fuel flow and SFC is investigated. Within that study, JSPK, CSPK and their 50% blends with Jet-A shows increment in thrust, reduction in fuel flow and improvements in SFC. The improvements in performance is the highest when 100% bio-SPK were used. Higher value of fuel's low heating value is observed to be a major factor in affecting high thrust generation. Furthermore, reduction in NOx emission and increment in CO also are observed. Generation of NOx considered in the study is based on thermal-NOx, in which the production of NOx has relationship with flame temperature within the combustion chamber. High flame temperature will generate high NOx. During combustion process, flame temperature of the bio-jet fuels reduces in compared to Jet-A thus generation of NOx reduces. However lower flame temperature causing the formation of CO increases. CO is formed by incomplete combustion. Due to low flame temperature produces for bio-jet fuel, oxidation of carbon atom is incomplete thus generate high CO.

3.0 METHODOLOGY

The chapter presents flowchart and discussion on methods used in conducting the study. Computer tool used for the evaluation will be introduced. Data used for the validation process will be presented.

3.1 Flowchart

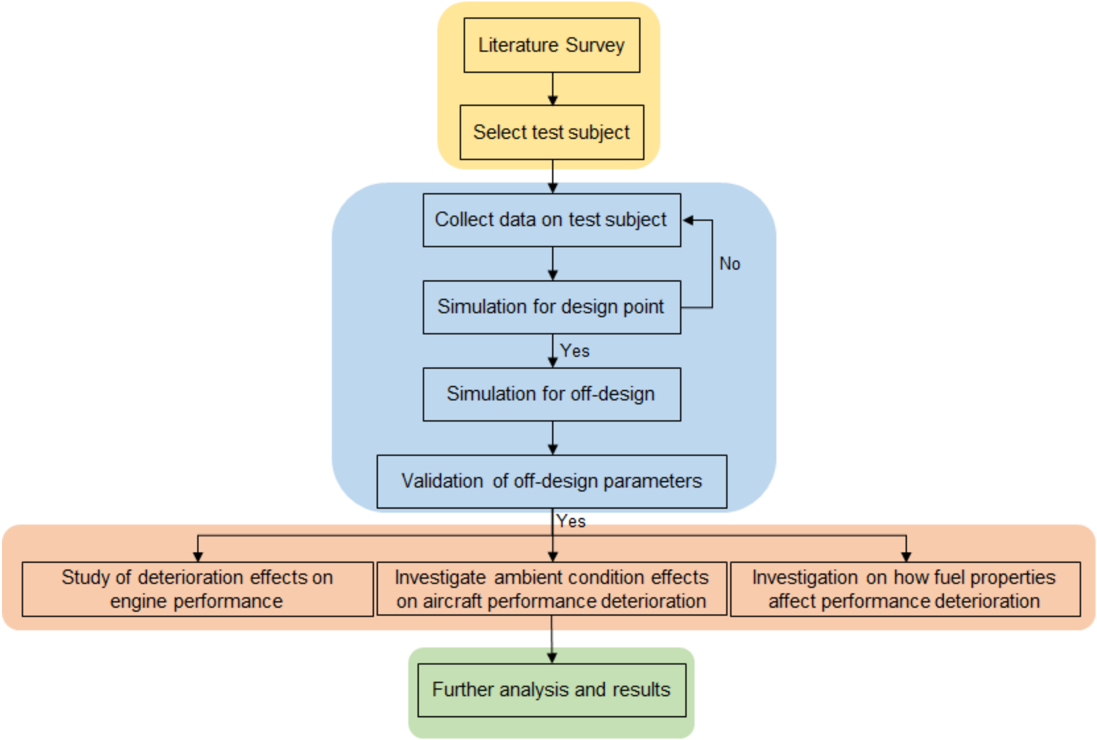

Figure 3: Flowchart showing the procedure of the research

Figure 3 shows the flowchart representing tasks performed upon conducting this research study, which includes several phases.

The first phase is about conducting literature survey to identify research on the topic. A test subject (existing gas turbine aero-engine) is then selected based on popularity and ease of information obtainment, followed by the collection of data for operational clean engine of the selected test subject from reputable source(s). With that, the CFM56-3 turbofan engine is then selected. Here the 1st phase of the project will end.

The second phase starts by the collection of data for the operational clean engine of the selected test subject from reputable source(s). Then the verification of the data obtained will be done. Simulation for design point is performed using GSP11 to verify with data obtained from literature surveys. Another test subject will be selected if the simulation result deviates from the operational data by a large margin. If the simulation result is within an allowable tolerance, the simulation for off-design for that exact engine will then be performed. The off-design simulation results will then be validated with existing published journals or data available.

The third phase of the project will be done by performing simulations of the verified model for different test cases which are; 1) Investigate the effect of deterioration on engine operational parameters, 2) Investigate the effect of ambient condition on deteriorated engine performance and 3) Investigate the performance of bio-jet fuel on deteriorated engine.

Finally, the results obtained from the simulation will be analyzed in the final phase.

3.2 CFM56-3 Turbofan Engine

CFM56-3 is chosen in conducting this research study. The CFM56-3 turbofan engine is a high-bypass turbofan engine made by CFM International (CFMI), with an announced thrust rating from 82.3 to 105 kN. The CFM56-3 is the first derivative of the CFM56 family series, where it is initially designed for Boeing 737 Classic series (-300/-400/-500). CFM56-3 has a double spool configuration, consisting of the common configuration with a fan, booster (low pressure compressor), high pressure compressor, combustion chamber, high pressure turbine, low pressure turbine and exhaust[40] as shown in Figure 4.

According to CFM International, the CFM56 series is the most commonly used and sold engine to date[41]. Hence making the CFM56-3 being one of the commonly found aircraft engine. Also, many other studies has been done onto the CFM56-3, and those studies contain much more detailed information and test data. These are the main reasons why the CFM56-3 turbofan engine is chosen as the test subject for this research.

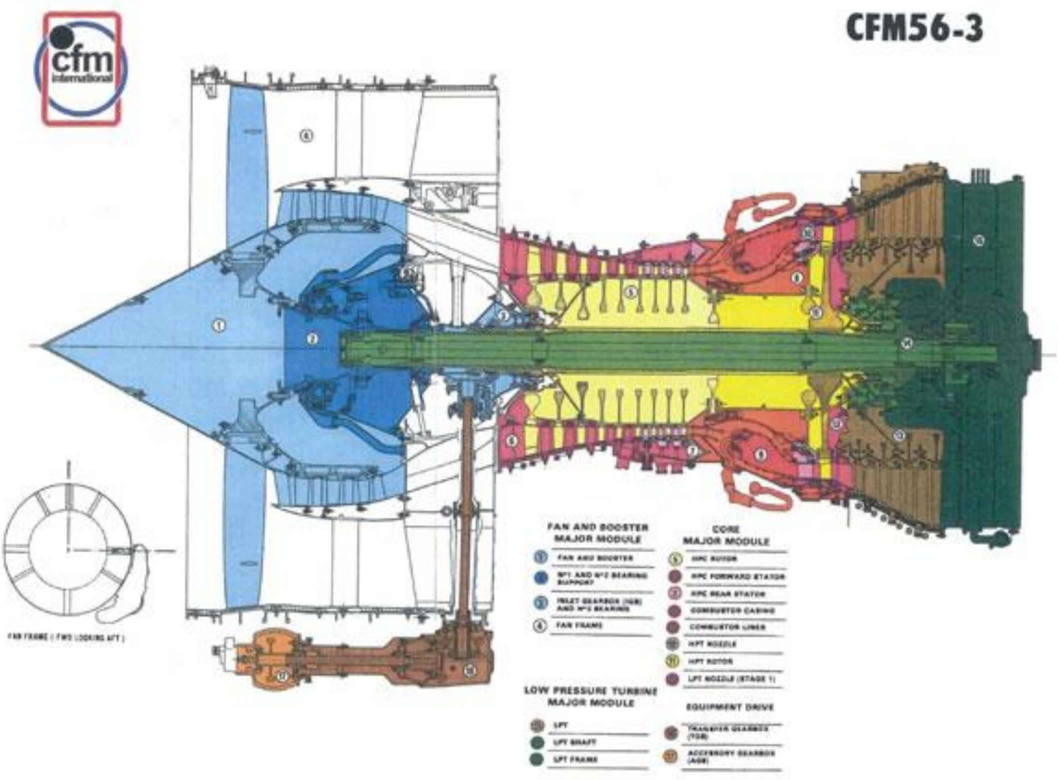

Figure 4: CFM56-3 configuration [Source: CFM International]

3.3 Modelling CFM56-3

3.3.1 Comparing GSP11 with GasTurb 11

There are a few suitable software available to perform engine performance study. Two most commonly used gas turbine simulation software are GasTurb and GSP11.

Gas Turbine Performance (GasTurb) is a gas turbine cycle program that simulates the most important gas turbine configurations used for propulsion or power generation. In general, GasTurb has a very user-friendly environment, where it comes with a manuals, journals and tutorials. User usually starts by selecting a type of engine from its library (turbo-jet, turbofan, etc.) and the type of calculation (on-design or off-design)[42, 43] as shown in Figure 5 . After the input of the engine parameters, one condition can be simulated and results can be obtained.

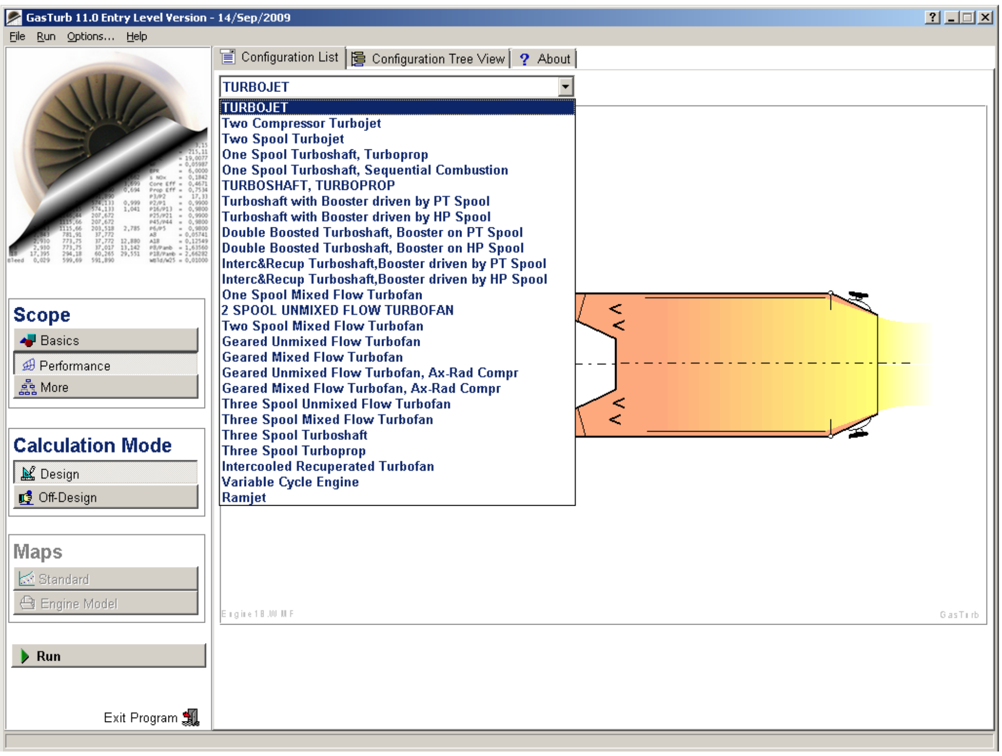

Figure 5: Simulation initiation process in GasTurb 11