Monitoring of Deterioration in Line Replaceable Units of Auxiliary Power Units

by

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Preface

While the work on this project proved more challenging than initially expected, it was extremely rewarding. I would like to thank EPCOR for providing me with this opportunity, as well as my supervisors Wilfried and Oscar for their guidance. Additionally, I would like to thank everyone at the company who helped me with more specific questions about APUs.

Georgi Rulev
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Abstract

Line replaceable units (LRUs) of auxiliary power units (APUs) are parts which can be quickly swapped while in between flights. Some of the LRUs on the Honeywell 131-9B APU, particularly the starter-generator, cause a lot of operational problems and unscheduled removals of the APU, which is why their condition needs to be monitored. By monitoring certain flight parameters, most importantly the exhaust gas temperature, EGT, and the start time, the condition of the starter-generator can be evaluated, which can be used to improve the maintenance, repair and overhaul (MRO) process, reduce downtime and extend the overall life of the APU. The data from one engine start is used as a baseline for a healthy APU, after which a gas path model is used to estimate the reduction in power during startup of a degraded APU. With the power reduction of each component known, the increase in start time can be attributed to a degraded starter-generator and/or a degraded turbine. An increase in EGT of roughly 150 $^{\circ}C$ could potentially indicate the APU is unable to start due to a severely degraded turbine. Additionally, it has been noticed that trends in other engine parameters are linked to the condition of LRUs (for example a sudden spike in oil temperature is likely caused by a faulty temperature control valve).

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
ACARS	Aircraft Communications Addressing and Reporting System
ACMS	Aircraft Condition Monitoring System
ANN	Artificial Neural Network
APU	Auxiliary Power Unit
BAV	Bleed Air Valve
CBM	Condition Based Maintenance
CMM	Component Maintenance Manual
DMM	Data Memory Module
ECU	Electronic Control Unit
EGT	Exhaust Gas Temperature
ETOPS	Extended-range Twin-engine Operations Performance Standards
FCU	Fuel Control Unit
FMEA	Failure Modes and Effects Analysis
GPA	Gas Path Analysis
IGV	Inlet Guide Vane
LRU	Line Replaceable Unit
MES	Main Engine Start
MRO	Maintenance Repair and Overhaul
NN	Neural Network
OEM	Original Equipment Manufacturer
SCV	Surge Control Valve
TCV	Temperature Control Valve

Symbols

Symbol	Definition	Unit
H	Health parameter	[%]
I	Shaft inertia	[kg·m^2]
M	Mach number	[-]
N	Shaft speed	[%]
P	Power	[W]
Q	Torque	[N·m]
T	Temperature	[K]
W	Mass flow	[kg/s]
p	Pressure	[Pa]
ρ	Density	[kg/m^3]
α	Angular acceleration	[rad/s^2]
ω	Rotational speed	[rad/s]
η	Efficiency	[-]

Subscripts

Subscript	Definition
2	Compressor Inlet
3	Compressor Outlet
4	Turbine Inlet
5	Turbine Outlet
b	Bleed
c	Compressor
$corr$	Corrected Value
f	Fuel
lc	Load Compressor
s	Static
st	Starter
t	Turbine
tot	Total

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Introduction

Aircraft maintenance is a complex, time-consuming and expensive task, which is why airlines strive to make it more efficient. In order to maximize the availability of a fleet, minimizing downtime is key; therefore improvements in the maintenance, repair and overhaul (MRO) process are very sought after. Additionally, cost is also a driving factor in this process.

One aspect where time can be saved is in the planing and scheduling of a MRO activity by knowing in advance what the specific tasks are and what replacement parts will be needed. This also allows maintenance to be performed before critical failure in an aircraft system happens. The challenge that arises is to reliably estimate the degradation of the system and its components. One of the systems onboard commercial airliners is the auxiliary power unit, or APU. While not as critical to the aircraft mission as the main engines, APUs are necessary to start the main engines, provide bleed air for the air conditioning packs or generate electrical power. Being one of the more complex systems onboard an aircraft, the APU has several important failure modes and requires extensive troubleshooting and testing. Depending on the size of the airline, it might be more economically sensible to have an external company maintain and service the APUs of the fleet instead of investing in all the equipment to repair them in-house.

Established in 1999 EPCOR (European Pneumatic Component Overhaul and Repair) is a licensed MRO provider for APUs, as well as pneumatic components. They service APU models from Honeywell and Pratt and Whitney. While it is a subsidiary of Air France Industries-KLM Engineering, EPCOR services APUs from a wide variety of airlines. To improve the MRO process and reduce turnaround, the company has started to implement APU condition monitoring tools. Thus, deterioration of the APU can be observed and it can be repaired before it operates too much in highly degraded regime. Currently, core APU health can be monitored but it is not representative of the various subsystems of the APU. Most notably, line replaceable units (LRUs) constitute a large portion of the APU and also affect its performance. These functions of the LRUs range from starting the APU to providing cooling and regulating fuel and air flow. It is therefore desirable to extend the condition monitoring capabilities to include LRUs. It is suspected that LRUs also affect the overall health of the APU, so replacing them before they fail could potentially extend the life of the APU, as depicted in Figure 1.1.

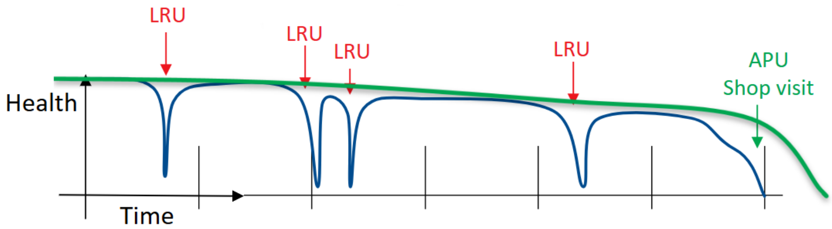


Figure 1.1: APU health over time if the LRUs are let to fail (blue line) and if they are replaced before failure occurs (green line)

The goal of the research is to improve the the efficiency in the MRO process of APUs by monitoring engine performance and deterioration of LRUs before they fail. This would both maximize the time the APU can be operated safely, as well as minimize unscheduled maintenance and repair, thus saving costs. With this objective in mind, the following research question will be investigated:

How can the condition monitoring, diagnostics and prognostics of line replaceable units on the Honeywell 131-9B auxiliary power unit be improved using on-wing performance data?

2

Literature Review

2.1. Auxiliary Power Units

An auxiliary power unit (APU) is a small gas turbine that provides electrical and/or pneumatic power to an aircraft. It is essentially a constant speed (corrected speed, not actual) turboshaft engine, which drives an electric generator, and on some models, a load compressor, which delivers bleed air to the aircraft (a simplified schematic can be seen in Figure 2.1). Typically, the APU is in use while on the ground, i.e. when parked or taxiing, however it is also used as an emergency power source (for example in case of a main engine failure). On routes where redirecting to an emergency landing site is longer, such as on transoceanic flights, twin engine airliners have to be compliant with ETOPS regulations (Extended range Twin-engine Operations Performance Standards). Specifically, the APU needs to be started to provide additional power in case of a single engine inoperative. When looking at the Honeywell 131 series, which are used on narrow-body airliners, they operate on the following modes:

- **Startup:** The startup phase of the APU is characterized by a profile which determines what happens at different shaft speeds (see Figure 2.3)
- **Idle:** When idling, the APU supplies no bleed air and little to no electrical power to the aircraft
- **Main Engine Start (MES):** During the MES sequence, the APU prioritizes bleed air supply to start one of the main engines over electrical power and is usually the most demanding in terms of power output.
- **Environment Control System (ECS):** In ECS, the bleed air is used for air conditioning of the cabin; electrical power is also available for lighting, communications, etc.

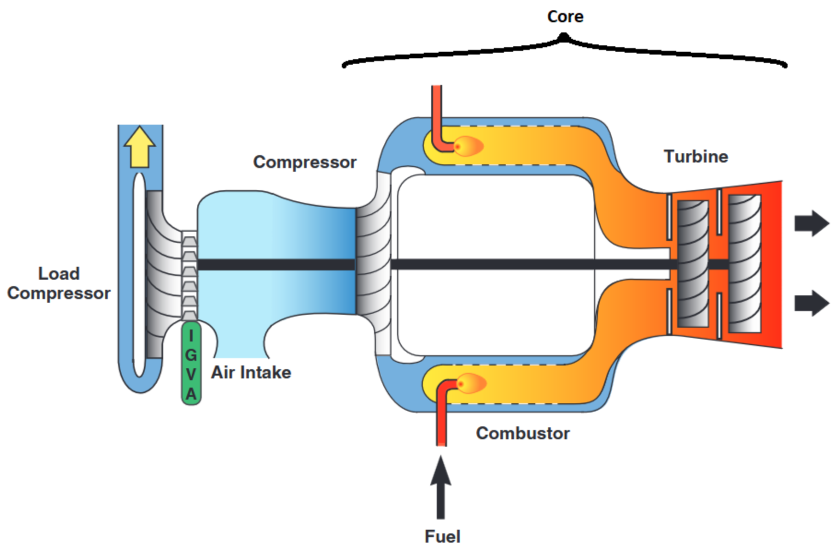


Figure 2.1: Simplified schematic of an APU [1]

Figure 2.2: Honeywell 131-9B APU

2.1.1. Startup Sequence

The starting phase of an APU contains critical information about the health of certain systems (such as the starter system [2, 3]). If we look at the start sequence of the Honeywell 131-9B in Figure 2.3, we can see what events happen at different shaft speeds. Furthermore, we can analyze test cell data to know the power levels of the different components and their contribution to the acceleration in different speed regions. Knowing this, we can potentially distinguish between core component and starter degradation.

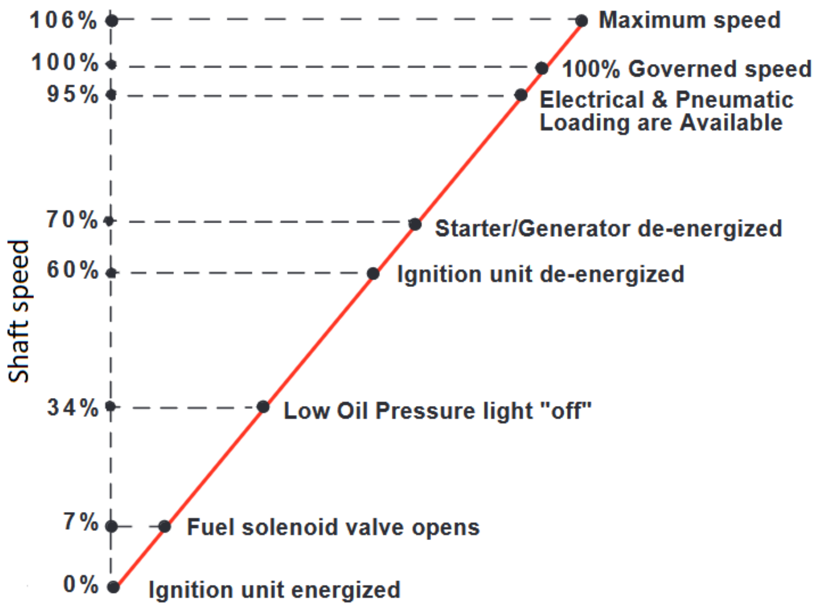


Figure 2.3: Start sequence of the Honeywell 131-9B

2.2. Maintenance Concepts for Auxiliary Power Units

Because APUs are not flight critical, airlines usually operate them until failure. This ”run-till-fail” approach has significant downsides however. A failed APU has very high repair costs on average, not only due to the severity of the damage, but also the inability to plan for it which leads to undesired downtime of the aircraft. For this reason, airlines have started to look into ways to avoid failure. The simplest way is to adopt a regular service interval for the APU. For example, life limited parts, or LLPs, have a set number of cycles they can be used, after which they need to be replaced. Such parts are for example the compressor, turbine and shaft. It is also possible to use error messages from the APU control unit to determine if a part or components is in need of replacement.

2.2.1. Corrective Maintenance

The simplest approach to maintenance is to use the APU until it fails. The downside is that the downtime of the system will always be unscheduled and the parts needed for repair have to be ordered on the spot. For large operations, these uncertainties imply more expenses and downtime, which is why more advanced approaches to maintenance are being developed.

2.2.2. Condition Based Maintenance

Condition based maintenance, or CBM, relies on performance data to determine whether the system operates within acceptable margins. This allows airlines to operate APUs longer before they fail and need expensive repair. It is also possible to schedule removal dates better when using condition based maintenance, so that they coincide with the routine aircraft checks.

2.2.3. Predictive Maintenance

The step after CBM is predictive maintenance. It builds up on condition based maintenance by also providing an estimate for the remaining life of the APU. This allows for an extended time on wing, while at the same time allowing the airline to plan the APU downtime according to their needs. Currently, Honeywell provides a service for predictive maintenance called PTMD (Predictive Trend Monitoring and Diagnostics) [4]. Among the tool's capabilities is the ability to relate APU performance measurements to LRU deterioration. More specifically:

- Estimate fuel nozzles health based on exhaust gas temperature (EGT) and peak starting EGT trends
- Estimate oil cooler and temperature control valve health based on oil temperature trends
- Detect IGV assembly faults based on inlet guide vane (IGV) position trends
- Detect fuel flow divider faults based on peak starting EGT trends
- Estimate starter-generator health based on starting time trends
- Detect SCV faults based on surge control valve (SCV) position trends
- Detect inlet temperature sensor faults based on inlet temperature trends

Since details about this tool are unknown, its fidelity cannot be confirmed for diagnosing all LRUs listed.

2.3. Condition Monitoring

Keeping track of the APU performance parameters and determining the health of the system based on this data is the essence of condition monitoring. Modern passenger aircraft have onboard systems, such as ACMS (Aircraft Condition Monitoring System), that ensure the engine is running normally by measuring performance parameters. The aircraft creates reports containing these parameters, which can then be forwarded to the MRO provider; at EPCOR, the data is stored and used in the Prognos for APU® condition monitoring tool. Most of the time, the OEM specifies the acceptable range for various parameters such as EGT, oil temperature, starting time, etc., however airlines can decide to implement other values if for instance they operate in very different climates which put additional strain on the APU (for example the polluted airspace over China and India, or the hot and dusty environment in the Middle East and North Africa).

2.4. Fault Detection and Isolation

When performing diagnostics on hardware systems, there are typically two main categories: model-based and data-driven. While a model-based approach is quite reliable in the sense that the algorithm is known and can be adjusted to improve its accuracy and reduce false alarms, it requires physical knowledge of the system, which often might not be available. In contrast, a data-driven method can be developed without this knowledge, however its performance is dependent on the quality of the training data. It is also unknown how the algorithm works on a low level, so edge cases might lead to unpredictable behavior [5].

2.4.1. Model-Based Approach

Model-based methods use physical knowledge of the system and are based on equations that model the relationships between its components. This means that historical data is not needed. The downside of model based methods is that physical understanding is needed of the relation between the different system components. For engine core components, the governing equations are known, so the effect of their deterioration can be modeled through the conservation equations. A common model-based approach used to determine the health of components in APUs is gas path analysis (GPA) [6]. The GPA method consists of measuring deviations in temperature and pressure along the gas path inside the engine and trying to find values for the health parameters of the core components which correspond to the deviations.

Modern applications of GPA can be found in adaptive modeling tools, such as GSP [7]. Adaptive modeling consists of tuning the health parameters of different components so that the performance of the thermodynamic model is closest to the real world measurements of the engine. The way GSP approaches the problem is through a system of equations like Equation 2.1. The functions F_1, ..., F_n are based on the conservation laws, with s_1 to s_n being the states at different stations in the engine (thus the equations $F_1(s_1)$ to $F_n(s_n)$ represent the reference engine model). The functions f_1, ..., f_m are the adaptive modeling equations needed to fit the deteriorated engine model to the measured data. h_1 to h_m are the deterioration factors that need to be calculated. The tolerances are set by the parameters ε (typically the tolerances ε for the reference model would be much smaller than the tolerances ε_m for the adapted model).

$$\begin{array}{cccccccc}
F_1(s_1)+ & \cdots & F_1(s_n)+ & F_1(h_1)+ & \cdots & F_1(h_m) & = & \varepsilon \\
\vdots & & \vdots & \vdots & & \vdots & & \vdots \\
F_n(s_1)+ & \cdots & F_n(s_n)+ & F_n(h_1)+ & \cdots & F_n(h_m) & = & \varepsilon \\
f_1(s_1)+ & \cdots & f_1(s_n)+ & f_1(h_1)+ & \cdots & f_1(h_m) & = & \varepsilon_{m,1} \\
\vdots & & \vdots & \vdots & & \vdots & & \vdots \\
f_m(s_1)+ & \cdots & f_m(s_n)+ & f_m(h_1)+ & \cdots & f_m(h_m) & = & \varepsilon_{m,m}
\end{array} \tag{2.1}$$

A gas path analysis can also be performed by using an optimizer to find the deterioration factors of the engine components. A recent study suggests it is possible to determine 10 health parameters using only 6 gas path sensors by using an evolutionary algorithm [8]. While this approach is useful when fewer engine parameters are measured, it requires data for multiple operating points.

2.4.2. Data-Driven Approach

When physical relations between component health and system performance is unknown, data driven methods are a viable alternative. Since historical data is available, trends within the data can be analyzed and connected to deteriorating LRUs. Furthermore, if enough data is available, it is possible to implement machine learning algorithms to classify engines based on the deteriorating component.

Statistical Analysis

Based on the understanding of the workings of the system and the available historical data, a statistical analysis of an airline fleet (such as the KLM 737 aircraft) can already provide a good estimate of the health of certain LRUs. When observing the evolution of the engine parameters, any sudden change or outlier is indicative of some anomaly. Simple time series plots of parameters such as EGT can often provide insight into probable problems in the APU.
One tool that is often used for highly dimensional problems is principal component analysis (PCA). It allows us to reduce the number of input variables by selecting linear combinations of the original variables that contain the most information. This simplification can be used both as a preprocessing step of the data, which will then be used in another algorithm, and a tool to find boundaries between

different clusters of data points. The logic behind PCA is to find the direction within a set of data points along which the variance is highest. This will be the first principal component. Every subsequent principal component has to be uncorrelated to the previous ones. This way, the first few principal components will contain most of the information contained in the dataset.

Machine Learning

With the advancement of machine learning and the continuous improvement in performance of computers, artificial neural networks (ANNs) have been of increasing interest in various fields, among which is system diagnostics. One recent study in diagnosing a turbofan engine compared the performance of 3 types of NNs; multi-layer perceptron (MLP), CNN (convolutional NN) and LSTM (long-short term memory) [9]. When looking at HPC surge margin and EGT estimations, the three models displayed similar performance, with root mean square errors of 0.0243, 0.0148 and 0.0177 respectively. On the other hand, predicting the remaining useful life is not as reliable, as seen in Figure 2.4. Here, the estimated remaining life of different engines (each line is a different engine). It should be noted however, that the predictions are getting close the actual value when the engine approaches its end of life, which is when they are most needed.

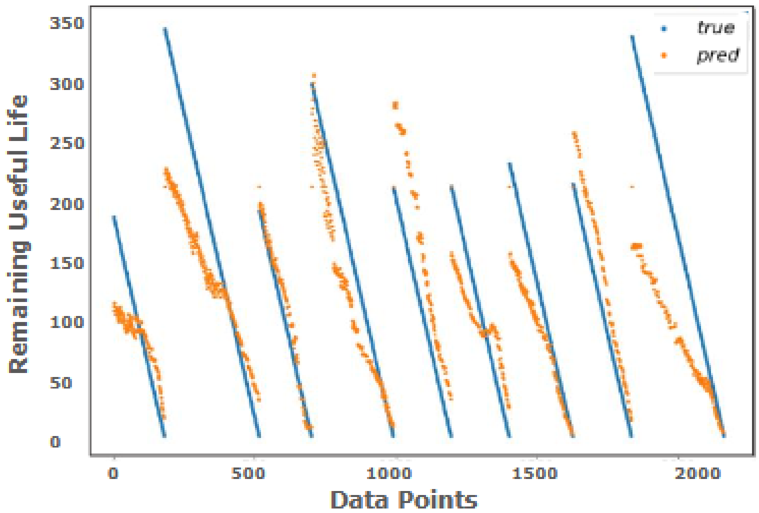


Figure 2.4: Prediction vs true values of remaining life (training sample-left, test sample-right) [9]

It is important to mention that while ANNs show some promise in diagnostics of turbofan engines, there are some differences compared to diagnostics of APUs. Firstly, APUs are smaller and much simpler engines. The number of onboard sensors they have is more limited to increase reliability. This means that much less data is available for the NN to process. For this reason, machine learning methods will not be considered further in this study.

3

APU Condition Monitoring by EPCOR

As mentioned previously, fast and efficient APU servicing is crucial for EPCOR in order to maximize profitability. By servicing the APU before failure occurs, the severity, and therefore cost of the servicing will be lower; the overall APU health will also remain sufficiently high for longer, increasing the total life of the APU. In addition to this, condition based maintenance increases the reliability of the APU during missions. These factors have driven the company to develop tools for condition monitoring. One tool that is being used is called Prognos for APU®, developed in house. This is essentially a database that stores and visualizes the APU snapshot measurement data that is sent over by the airlines. Furthermore, it allows engineers to set limits for parameters and estimate when maintenance should be performed. The current capabilities of Prognos will be described later in this chapter, as well as areas where condition monitoring can further be implemented.

3.1. Available Data

It is important to outline what data will be used to develop condition monitoring tools for the APU. On one hand, we have the data that the aircraft provides, which is a snapshot containing engine performance parameters. This snapshot is taken a few times per cycle, once for each different mode of operation. On the other hand, we also know the state of each part of the APU once it comes in for servicing. This information is then used to determine the steps required for a complete maintenance, but it can also be analyzed to find correlations between the underlying cause of the shop visit and the APU performance data. Finally, there is also a test cell for APUs, which measures more performance parameters compared to the ECU alone. Normally, the test cell is used to certify an APU once it has been serviced, but it can also be used to validate a numerical model of the APU, or obtain time series data of the start-up profile for instance.

3.1.1. Snapshot Data from ACARS Reports

The snapshot data is communicated by the airlines in the form of ACARS reports. The data is then stored and displayed in Prognos, where graphs and fleet plots can be generated and analyzed. A snapshot is taken during every engine cycle at startup, idle, Main Engine Start (MES) and shutdown. Compared to other APU models, the 131-9B lacks data that is relevant to some LRU health monitoring. This includes oil level and consumption, both values of the EGT probes, turbine inlet temperature, all of the different valve commands, etc. This means that the health monitoring of certain LRUs is not feasible with the available data. The reports from the 131-9B model includes the following data (additionally, the ECU records event data, such as protective shutdowns and warnings):

- Exhaust Gas Temperature EGT and corrected EGT EGT_{corr}
- Fuel flow W_f and corrected fuel flow $W_{f,corr}$
- Corrected bleed pressure $p_{b,corr}$
- Corrected bleed flow $W_{b,corr}$
- Oil temperature T_{oil}
- Generator load

- Inlet temperature T_2 and pressure p_2
- SCV position
- IGV position
- Altitude h
- APU speed N
- Total pressure p_{tot} and dynamic pressure (also called delta pressure) Δp at the load compressor outlet
- Number of unsuccessful starts (cumulative, since repair)
- Start time t_{start}

Sometimes the messages associated to the event can provide additional useful insight to isolate the faulty LRU. For instance, a warning for high oil temperature can be used to focus on the lubrication system, more specifically the oil cooler and temperature control valve. Furthermore, when a protective shutdown is initiated, the last minute is recorded. This is especially useful when an start attempt is aborted, since the speed, fuel flow and exhaust temperature can be used to investigate the reason for the aborted start.

We should note that the format and content of the reports vary between various APU models, but can also be different between two identical aircraft operated by different airlines (e.g. Boeing 737 in KLM vs Transavia fleet). This adds some inconsistencies in the data, especially the KLM fleet; it can happen that more than half of the reports contain invalid data.

3.1.2. Shop Findings

When the APU arrives for servicing, it is inspected for the cause of the removal. The findings are then documented alongside the replaced/repaired parts and uploaded to the company servers. Because LRUs can be replaced while the APU is ”on-wing”, replacement dates and shop findings can be documented by either the airline or EPCOR. If a fault is known to be caused by an LRU, the LRU will be replaced on the line. This creates a challenge in terms of keeping a consistent record of the maintenance tasks performed on the APU. KLM for example would experience issues with the starter-generator on an aircraft and would therefore replace it on the line. This is not then shared with the MRO provider automatically.

3.1.3. Test Cell Data

The test cells at EPCOR have more sensors and continuously monitor the performance data, which is mainly used for certification purposes. However, the test cell data can also provide time series data, which be used for verification and validation of the diagnostic tools. One area of interest is investigating the startup profile of the APU in order to see the contribution of the turbine, compressor and starter to the shaft acceleration. This can help with determining if a slower or failed start attempt is caused by a degraded starter or core component.

3.2. Monitoring of APU Core

Previous studies within EPCOR have focused on monitoring the condition of the APU core components, more specifically the turbine [10]. Since very little is known about the temperature and pressure through the system (only inlet conditions and exhaust temperature), the study considered only the deterioration of the turbine in the form of isentropic efficiency reduction and assumed a constant compressor efficiency. The reasoning behind this is that the turbine will degrade faster than the compressor on average because of the extreme temperatures. The calculated parameter, called ”turbine efficiency” inside Prognos, does not represent the actual turbine efficiency, but rather represents the overall health of the gas generator (or core, gas turbine). We will later refer to this ”turbine efficiency” parameter as ”gas turbine health” H_{GT} to avoid ambiguity with the real turbine efficiency η_t. H_{GT} is very heavily correlated with the corrected EGT during MES.

Currently H_{GT} is used to estimate the remaining life of the APU and schedule a shop visit. Being subject to high temperatures and pressures, the hot section is usually the main reason for removal.

On occasions though, LRUs can cause problems such as accelerated degradation of the hot section, inability to deliver enough power to the aircraft, unforeseen shutdowns or even failure to start the APU, which is why it is desirable to include them in the APU condition monitoring capabilities.

3.3. Line Replaceable Units

While faults in some LRUs may allow the APU to remain operational for some time, it is desirable to service them in time and have an estimate of their health. If a certain LRU doesn't operate within desirable margins, it could lead to accelerated deterioration of core components as well (e.g. a clogged fuel nozzle causes uneven combustion inside the combustion chamber, which can lead to cracks forming in the combustor liner). LRUs of interest on the Honeywell 131-9B, ordered by number of repaired/replaced parts in the period 2019 - 2024 on the Boeing 737 fleets of KLM and Transavia, include the starter-generator (41, serviced on-wing), bleed air valve (34, serviced in shop), fuel nozzle (34, serviced in shop), oil cooler (16, serviced in shop), temperature control valve (12, serviced in shop) and lube module (10, serviced in shop).

In this section, we will list the main LRUs of the 131-9B APU. Each LRU of interest will be briefly described, along with its relevant failure modes and their effects on the system. This will help us identify which engine parameters will be helpful when diagnosing deteriorating LRUs. Among the LRUs listed below, the starter-generator is causing the most unscheduled removals, which means higher repair costs and longer servicing times. The starter-generator will have the biggest impact on improving the servicing process and it will therefore be the main focus of the research. The monitoring of the oil cooler, temperature control valve, surge control valve, bleed air valve and inlet guide vane actuator will also be discussed, however in a less rigorous manner.

3.3.1. Starter-Generator

Figure 3.1: Starter-generator

The Honeywell 131-9B is a somewhat rare example where the starer motor and generator are combined into one component, shown in Figure 3.1. The starter-generator consists of three pairs of rotors and stators which can either drive the engine shaft, or provide electrical power to the aircraft (three phase 400 Hz 115/200 V AC). The ECU determines the mode of operation of the starter-generator.

During a visit of the KLM Engineering & Maintenance shop where the start-generators are serviced, two main failure modes were identified: internal short-circuit, such as a shorted diode, or a worn adapter which connects the starter-generator shaft to the spline on the APU gearbox. Both of these failure modes do not exhibit a gradual reduction in performance, but rather a sudden failure which makes the APU unable to start at all. Predicting these two failure modes is essentially impossible, since they are somewhat random. It has been observed however, that in some cases warnings for clogged scavenge filter on the lubrication module (see Figure 3.8) are presented some time before a short-circuit in the starter-generator occurs. This event is shown in Figure 3.2. This behavior can be explained by the presence of some contaminants in the oil inside the starter-generator, which are likely to cause arcing. Since the scavenge filter only filters oil coming from the starter-generator, it is fair to assume that there is a high risk of starter-generator failure after a warning for a clogged scavenge filter. Recommending S/G inspection and flush in this case.

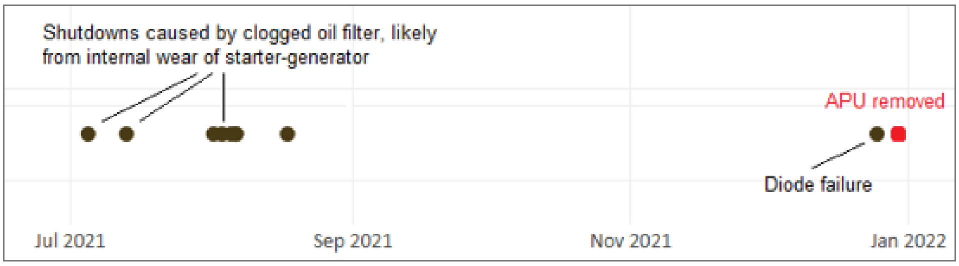


Figure 3.2: Clogged scavenge filter warning, followed by a shorted diode, forcing a shop visit

It would also be useful to determine how the gradual loss of performance of the starter-generator affects the start time of the APU. Heat, high speed and small vibrations over time can reduce the maximum torque the starter-generator can apply on the APU shaft. The causes could be a combination of worn windings, misalignment, damaged bearings.

Since the start time is one of the few recorded parameters, it we can potentially use it to estimate the health of the starter-generator. It has been noticed that the decrease in starter efficiency leads to a higher peak EGT [11, 12]. If the starter has degraded and takes longer to accelerate the APU in the low speed region, the reduced airflow will mean a richer fuel mixture for longer and the peak EGT will be higher. Peak EGT is typically between 20 and 30% shaft speed.

3.3.2. Bleed Air Valve

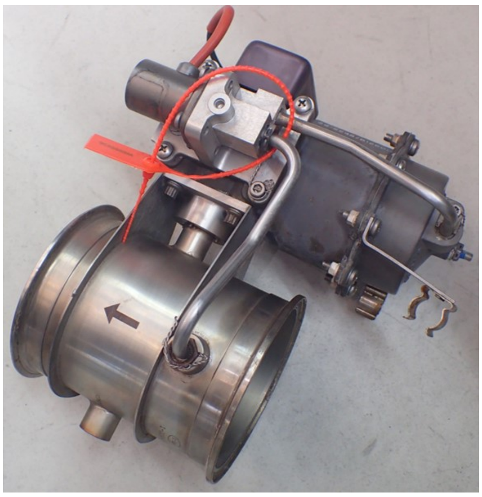


Figure 3.3: Bleed air valve (BAV)

The bleed air valve (Figure 3.3) is a pneumatically actuated butterfly valve that regulates the bleed air flow from the APU to the rest of the aircraft. When there is a demand for pressurized air from the aircraft, the valve opens and releases the bleed air towards the ducts in the aircraft, either for air conditioning or starting the main engines. A faulty BAV does not necessarily affect the operation of the APU, however it would make the aircraft unable to start its engines. Common modes of deterioration can be obstruction in the air tubes used to actuated the valve, air leak due to wear on the body, deformation of the diaphragm and cable chaffing. With the limited data available on-wing, we cannot determine the exact fault if there is one, however we may be able to determine if the valve opens sufficiently.

Because we do not measure the position of the valve directly, we have to see how a faulty BAV would impact another parameter. If the valve fails to open sufficiently when there is a high demand for bleed air, this would increase the static pressure at the load compressor outlet. During MES, where there is a high demand for bleed air, a stuck valve will decrease the surge margin of the compressor and trigger the surge control valve to open.

3.3.3. Fuel Control Unit

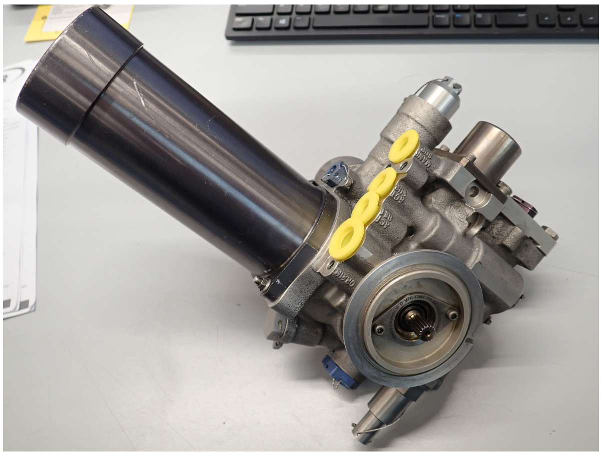


Figure 3.4: Fuel control unit

The fuel control unit, or FCU, shown in Figure 3.4, is an assembly consisting of a high pressure fuel pump, filters, fuel torque motor, flow meter, fuel shutoff solenoid. Its role is to supply pressurized fuel to the SCV and IGV actuators, as well as to supply fuel to the combustor. A detailed diagram of the FCU is shown in Figure 3.5. The fuel pump is mechanically linked to the APU shaft via the gearbox.

If the gear elements of the fuel pump degrade too much, the decrease in fuel pressure could impact the position of the SCV and IGV. Additionally, the fuel torque motor may need to open more to compensate for the decrease in pump performance. Another way the FCU could fail is a leaky valve, which could lead to a very high fuel flow to the engine. This means that a sudden abnormally high fuel flow is likely caused by a faulty FCU. However, without additional measurements inside the module itself, we cannot monitor the gradual deterioration of the FCU.

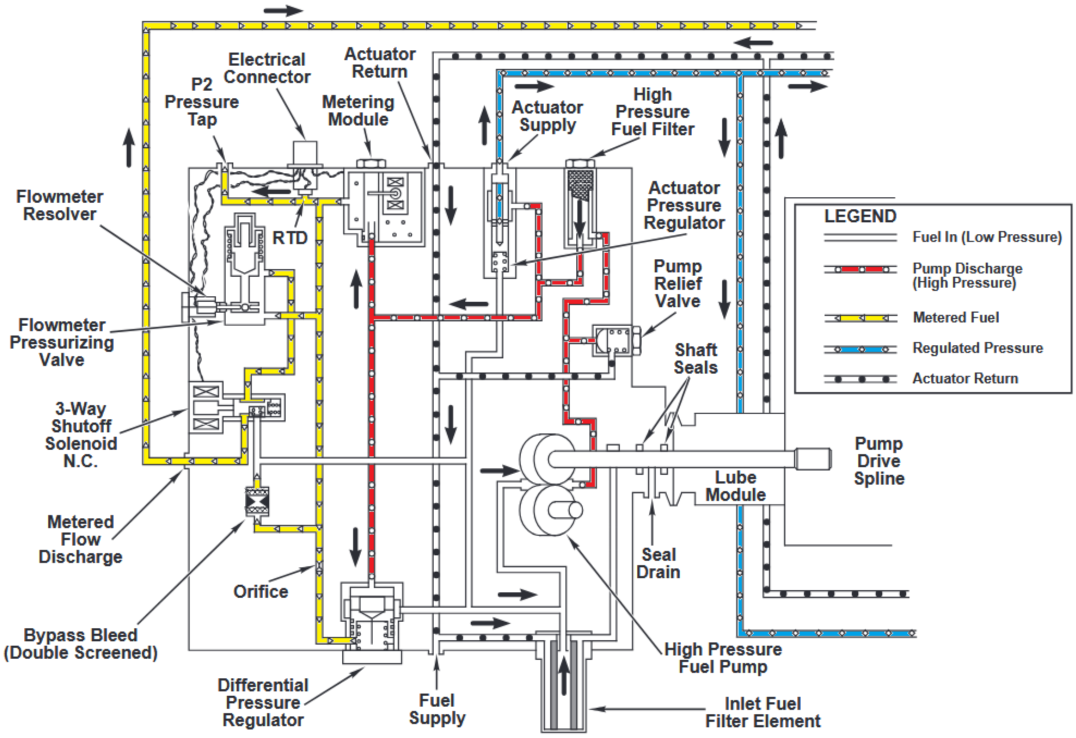


Figure 3.5: FCU diagram [1]

3.3.4. Ignition Unit

The ignition unit provides a spark to ignite the fuel during APU start. It consists of an exciter box, an ignition plug and a lead connecting the two. High voltage, combined with high temperature degrade the ignition unit, more specifically the ignition plug. On the 131-9B, there is a single ignition lead and ignition plug, so the APU cannot start if any of the components of the ignition unit fails.

Figure 3.6: Exciter box

Because the ignition unit is only excited until around 60% shaft speed, and a faulty ignition unit means the APU is unable to start, deterioration of the ignition unit cannot be measured without additional data (e.g. an acoustic sensor to monitor the sound signature of the spark [13]). For APU models with 2 igniter plugs, the engine can still start if one igniter fails. In this case, a large temperature gradient will be observed briefly. However, several factors make it very unlikely to measure this temperature difference. Firstly, the flow is mixed by the turbine stage before its temperature is measured. Furthermore, only two thermocouples are installed in the exhaust. Finally, only one snapshot is taken during the start phase, which is taken at peak EGT, which means the effects of igniter failure will have completely dissipated.

3.3.5. Inlet Guide Vane Actuator

The IGV assembly consists of 16 blades, each linked to a geared cylindrical rack which can adjust the position of the vanes. Its purpose is to regulate the airflow through the load compressor. During different phases, the aircraft may need less bleed air, so it is desirable to reduce the power required to drive the load compressor by reducing the airflow.

To change the angle of the vanes, there is an actuator that moves the rack. The IGV actuator is driven by fuel pressure from the FCU. The position of the actuator is monitored by the ECU, so any disagreement between the IGV command and position is detected. During APU start for example, the IGVs are held closed at 22°, whereas in MES mode, they are opened usually around 90°, depending on the ambient conditions.

3.3.6. Lubrication Module

The oil through the APU serves two purposes: to lubricate and cool rotating parts. The lubrication module provides the oil pressure to move it though the system. Figures 3.7 and 3.8 show the lubrication module and a schematic of its internal components.

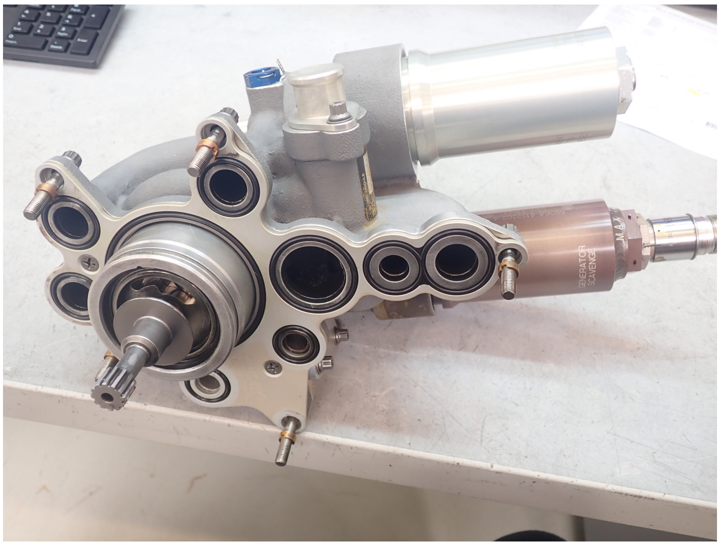


Figure 3.7: Lubrication module

Because the oil pump is driven by the same shaft as the fuel pump, deterioration in the lubrication module that increases the required torque will exhibit the same symptoms as for fuel control unit degradation. The pump itself consists of 7 gerotor pump elements (3 lube pump elements, 3 generator scavenge elements, 1 turbine scavenge element, see Figure 3.8). Since the working fluid inside the pump is a lubricant, it is fair to assume that on average, the lubrication pump will wear down slower than the fuel pump for example. Still, wear of the pumping elements will create gaps, therefore reducing the displacement volume and pressure. It is also possible that the scavenge pump elements suffer domestic object damage DOD (e.g. turbine bearing breaks and releases metal particles). It has been observed, that this bearing failure increased the oil consumption and causes sparking.

On each filter element there is a pressure difference indicator (on the lube element - indicator that pops up if filter is clogged; on scavenge element - delta P switch that sends signal to ECU). This allows to detect a clogged filter element. Additionally, there is a low oil pressure switch which sends a signal to the ECU if the pressure is too low (the exact pressure is unknown). These events can be used to troubleshoot problems, but they do not provide any data that can be used to monitor the health of the lubrication module continuously.

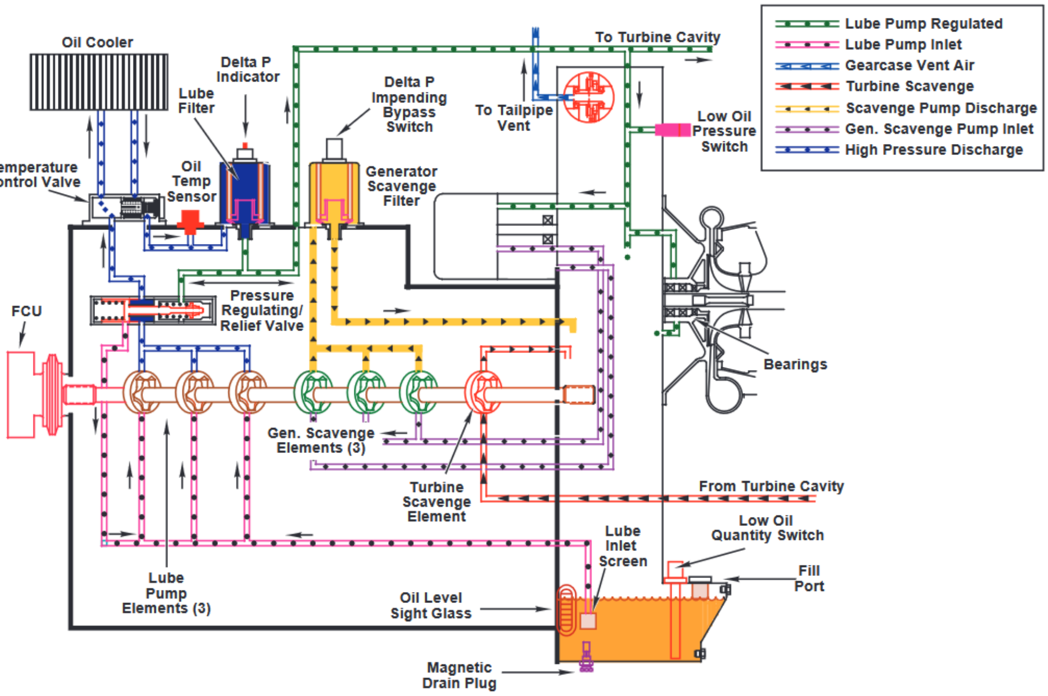


Figure 3.8: Lubrication module diagram [1]

3.3.7. Fuel Nozzles

There are 10 dual orifice fuel nozzles on the 131-9B APU. Their function is to create an even fuel mist in the combustor.

(a) Injectors

(b) Shrouds

Figure 3.9: Fuel nozzles

Any small obstruction or damage on the tip can have significant effect on the spray quality, which can cause hot spots to appear in the combustor. Furthermore, overall efficiency of the APU will be affected by this suboptimal spray pattern. Theoretically, this temperature gradient could be detected using the two EGT probes: if a large difference is observed over several cycles, this would indicate one or more fuel nozzles should be replaced. However, on the APU type we are investigating, only one EGT value is recorded. Without changing the logic of the ECU to record both EGT values, we cannot detect any temperature gradient at the turbine exhaust.

3.3.8. Oil Cooler

The function of the oil cooler is straight-forward; the hot oil coming from the sump is cooled using the air in the APU compartment.

Figure 3.10: Oil cooler

An oil cooler can experience two types of failure: obstructed airflow through the radiator, or an oil leak. This will lead to an increase in the oil temperature, or increased oil consumption respectively. Some APU models, like the 131-9B, do not measure oil quantity. Instead, a gauge is present that shows the oil level, but requires a visual inspection which cannot be done routinely due to the impractical location of the APU inside the aircraft. Instead, this inspection occurs on a schedule determined by the airline.

3.3.9. Temperature Control Valve

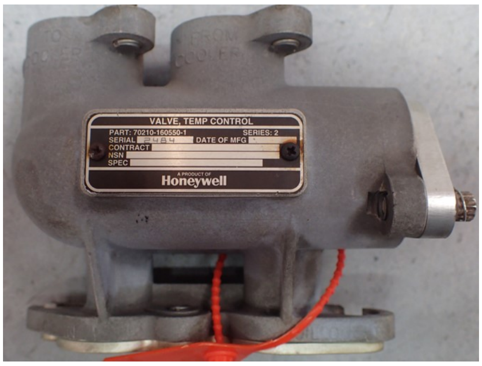


Figure 3.11: Temperature control valve

The purpose of the temperature control valve is to bypass the oil cooler when the oil is below a certain temperature. This reduces the load on the oil pump, for instance during APU start when the oil is still cool. In the event that the valve is stuck in the open position, this will cause a significant increase in oil temperature, potentially triggering a protective shutdown. If it is stuck in the closed position, oil will flow through the cooler even at low temperatures, which adds resistance that the oil pump needs to overcome.

3.3.10. Surge Control Valve

The surge control valve, as the name suggests, is used to control the surge margin of the load compressor. When there is no bleed air demand from the aircraft, the airflow through the load compressor is reduced, but is not zero. This means that, in order to prevent surge, the discharge air has to be directed somewhere. The surge control valve reroutes it to the APU exhaust.

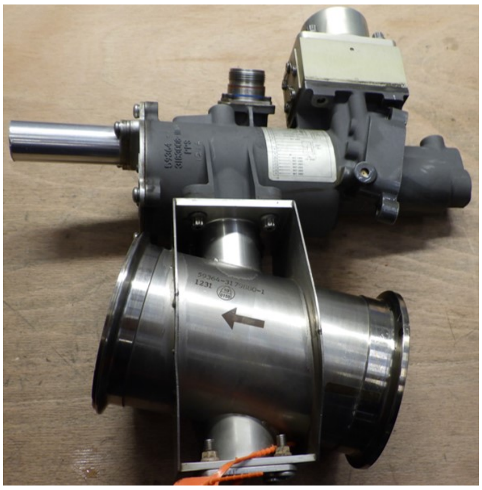


Figure 3.12: Surge control valve

The SCV is another fuel actuated part, which means that a deteriorating FCU could impact the valve position. Another possible failure mode is bleed air leaking into the APU compartment, which can reduce oil cooling. This issue is not restricted to the SCV, bleed air from the load compressor can leak through other holes/gaps, such as impeller scroll or tubes. Similarly to the IGV actuator, a disagreement between SCV command and position suggests a faulty SCV.

The low number of significant repair tasks on the SCV in the shop suggests it rarely malfunctions.

4
Improving the Condition Monitoring Capabilities

With the current condition monitoring capabilities at EPCOR discussed in chapter 3, we can now focus on the possible improvements of the toolbox. We've mentioned previously how the starter-generator is a problematic LRU that causes a lot of unscheduled removals. The repair is costly and frequent, which makes the starter-generator the main cost driver and therefore has been selected for further research. While some of its failure modes are sudden and cannot be monitored, we would like to know how its performance impacts the starting sequence of the APU in order to develop a health indicator for it. The hypothesis is that the starter-generator has significant contribution in the low-speed region of the starting profile, after which the gas turbine takes over and accelerates the engine up to 100%. This would mean that two health parameters are relevant here: the starter-generator health and the gas turbine health (H_{GT}). In order to determine the reason behind a longer start, we would like to investigate the start sequence. This requires the development of a thermodynamic performance model of the APU. Afterwards, we will create rules to monitor in section 4.3.

4.1. Gas Path Model

To address the gas path, a thermodynamic model of the APU was created using GSP 12. GSP is a generic modeling software dedicated to simulating various gas turbines; from industrial turbines in power plants to afterburning turbofan engines. It relies on design data of the turbomachinery components in the form of compressor and turbine maps to analyze the performance of the engine in different operating conditions. The process of creating the APU model can be described as follows:

1. Create a model of the isolated load compressor running at different shaft speeds and IGV settings (described in subsection 4.1.1). Since the load compressor is not a part of the cycle, its only influence on the system is the load it adds on the shaft. Analyzing the load compressor separately simplifies the calculations.
2. The output of the model is then used to create a map which relates shaft speed and IGV position to shaft power (the map is shown in Figure 4.3). The load of the load compressor on the APU shaft is added artificially in the APU model.
3. Create a model of the APU core as shown in Figure 4.1. Use MES load condition as design point, i.e. IGVs open at 90°, 65 kW electric load, 100% shaft speed.
4. After the APU has been sized, we create a series of steady-state points at different speeds, so as to simulate the starting sequence. This is not meant to recreate the real-world start (which requires a transient model), just to establish the power levels of each component at different speeds. Since the acceleration of the APU is relatively constant, the power levels of the different components in relation to each other will be very close. The development of a transient model implies knowing the inertia of the shaft, the control strategy of the control unit and an advanced model to simulate the sub-idle conditions (between 0% and 40% shaft speed) reliably, which was deemed unnecessary for the purposes of the study.

5. For validation, we use test cell data for two different load conditions (MES and ECS). Additionally, time series data from an APU start is available, which will be used later when diagnosing the starter-generator.

In order to simplify the APU model, a map was created to model the shaft load from the load compressor at different speeds and IGV positions. This load was then added to the APU shaft as power offtake from the turbine. Additionally, the starter-generator also adds some load (with a negative sign if it is operating as a starter). The model setup is displayed in Figure 4.1.

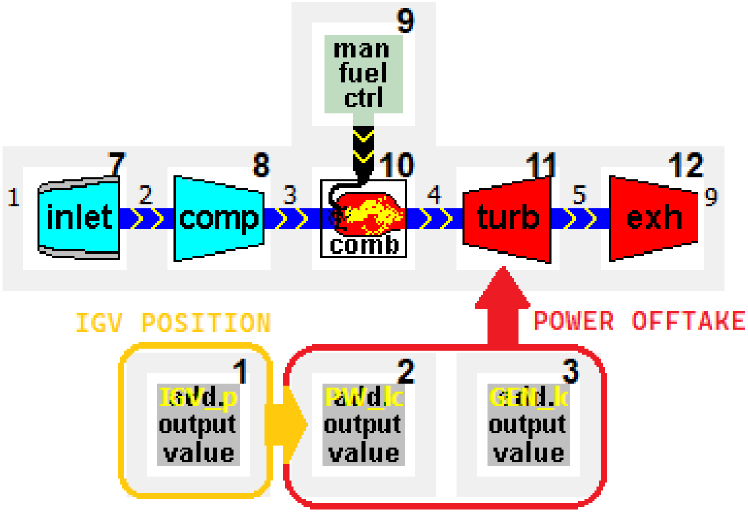


Figure 4.1: Simplified GSP model of the APU; the IGV setting, as well as the starter(-generator) load, are determined by the shaft speed via a lookup table

4.1.1. Load Compressor

As mentioned above, the load compressor, which supplies pneumatic power, is modeled separately from the APU core. The GSP model is shown in Figure 4.2. A series of steady-state simulations at various shaft speeds and IGV positions can be used to create the power map shown in Figure 4.3.

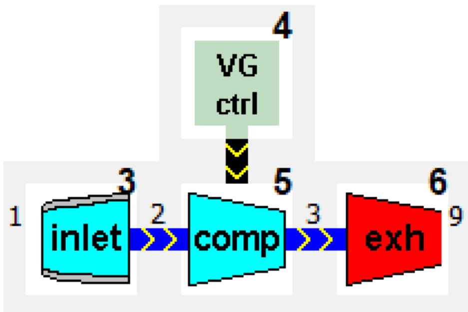


Figure 4.2: GSP model of the isolated load compressor with a variable geometry controller

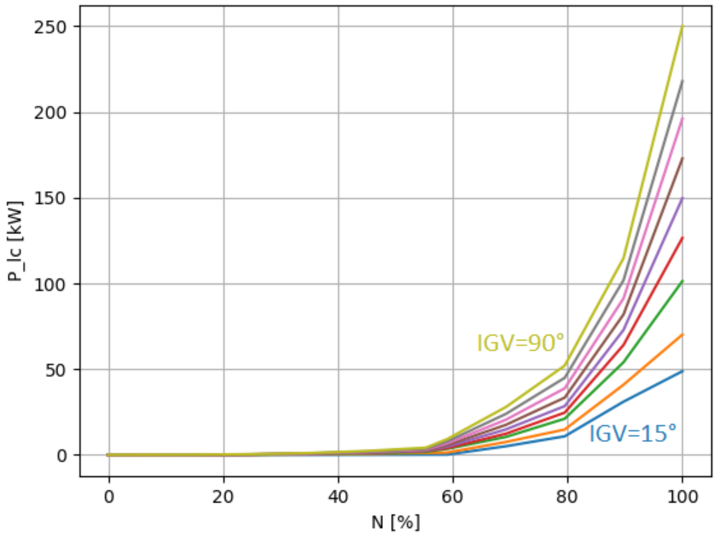


Figure 4.3: Power of the load compressor at different shaft speeds and IGV settings

4.1.2. Compressor Deterioration

The deterioration of the compressor could be caused by fouling, corrosion, rubbing, all of which reduce the efficiency and mass flow. Wear of the impeller or shroud creates gaps which means not as much air can be forced through the compressor. This explains the lower mass flow and efficiency. Within GSP, these deterioration factors can be applied to the component maps, which are scaled to this new degraded condition. The deterioration factor ΔH_c implies $\Delta\eta_c = \Delta H_c$ and $\Delta W_c = \Delta H_c$.

4.1.3. Turbine Deterioration

Due to the extreme temperatures, the turbine degrades more rapidly than the compressor on average. Erosion of the blades increases the cross sectional area, which increases the mass flow through the turbine. However, less work can be extracted, so the efficiency is lower.

Similarly to the compressor, the deterioration factor ΔH_t implies $\Delta\eta_t = \Delta H_t$ and $\Delta W_t = -\Delta H_t$.

4.1.4. Combustor

Combustor degradation could be expressed in terms of combustion efficiency or thermal efficiency: a low fuel spray quality causes incomplete combustion, whereas a damaged combustor liner would mean that more heat is lost to the environment.

Effects of combustor deterioration will not be taken into account in the model.

4.2. Starter-Generator Performance Analysis

In order to estimate the degradation of the starter, or starter-generator in this case, the profile of the APU during the start sequence is crucial. While this data is not usually recorded by the ACMS, it is recorded whenever a protective shutdown occurs and can also be obtained from APU tests run at EPCOR in the test cell. It is important to determine whether a slower or failed start is caused by the starter or a core component.

We use the shaft work balance to estimate the contribution of each part during the start sequence:

$$I\alpha\omega = P_{tot} = P_{st} + P_t - P_c - P_{lc} = P_{st} + P_{surplus} - P_{lc} \tag{4.1}$$

Using the GSP model shown in Figure 4.1, we can calculate the different terms in Equation 4.1. One difference with the model shown in the figure is that no external load will be applied to the shaft ($P_{offtake} = 0$) and the power balance equation will be disabled (note: the term surplus power will be used later $P_{surplus} = P_t - P_c \neq 0$). Changing the model this way makes the simulation more stable at low speeds. The model still fails to converge to a solution below 30% speed. Incomplete and unstable combustion (flames coming out of the exhaust) could explain why a steady-state solution does not exist at very low speed.

Because not enough details about the APU are known to create a dynamic model, a steady-state series of simulations of the start sequence was constructed. The model was run through various shaft speeds and turbine inlet temperatures. We can then see the power levels of the different components at different operating points.

With the EGT values measured in the test cell (see Figure 4.4), we can match them to the corresponding points from the simulation. The EGT is used as input to obtain the fuel flow and surplus power (from Figure 4.5 and 4.6 respectively). The surplus power obtained from the model is shown in Figure 4.7 next to the power of the load compressor and starter.

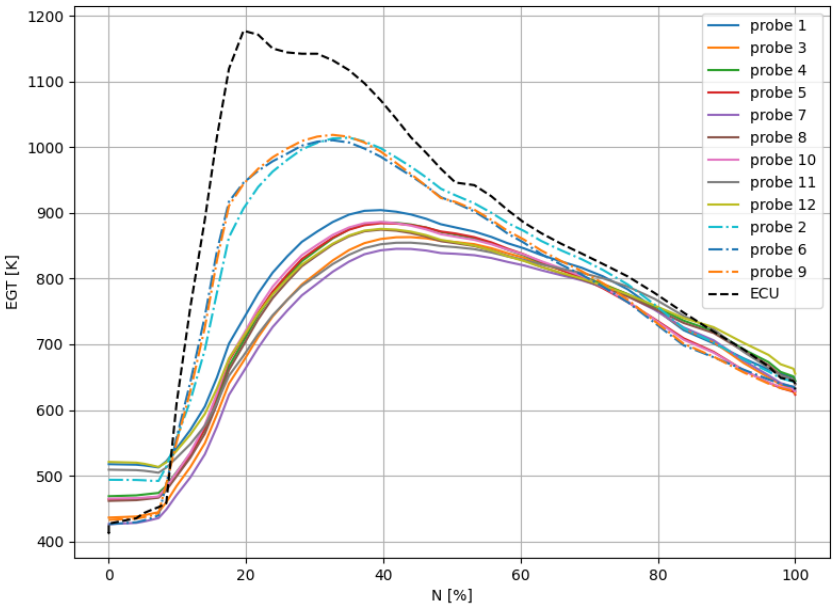


Figure 4.4: EGT during the APU test start; measured by the external test probes 1-12 and by the APU thermocouples (ECU)

GSP also allows us to apply deterioration factors to the turbine and compressor maps, so we can estimate the resulting power drop and the increase in start time. The nominal starter power will be measured in a test cell, and then compared to the power levels of the turbine and compressor.

Firstly, we calculate $P_{surplus}$ of the reference healthy engine. To do this we will take the EGT values from the test cell (Figure 4.4) and match them to the EGT values of the GSP model. We should note that the reason for the large difference in the EGT measured by the ECU and the external probes is their location: because the EGT thermocouples of the APU are very close the the turbine exhaust, the flames coming out of the combustor heat them up more, whereas the probes of the test stand are located further downstream, where the combustion is complete.

Taking the EGT measured by the ECU as input (EGT_0), we obtain the fuel flow at a given shaft speed (Wf_1), as well as the surplus power $P_{surplus}$ of the reference engine. Because the controller is open-loop during start, the fuel flow Wf_1) will remain the same for the deteriorated APU model; this then gives us the EGT at that speed for a deteriorated APU (EGT_1). With EGT_1 obtained from Figure 4.5, the reduction in surplus power can be observed in Figure 4.6.

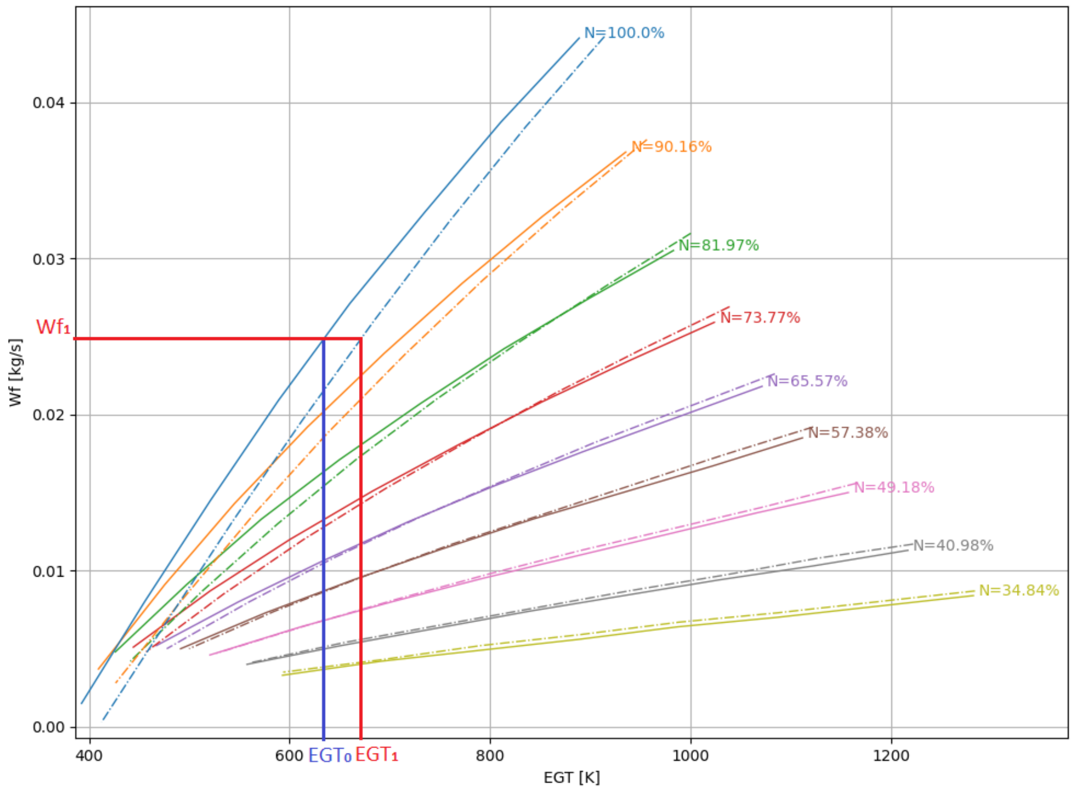


Figure 4.5: Fuel flow Wf at different shaft speeds for a healthy (solid line) and deteriorated (dashed line) APU

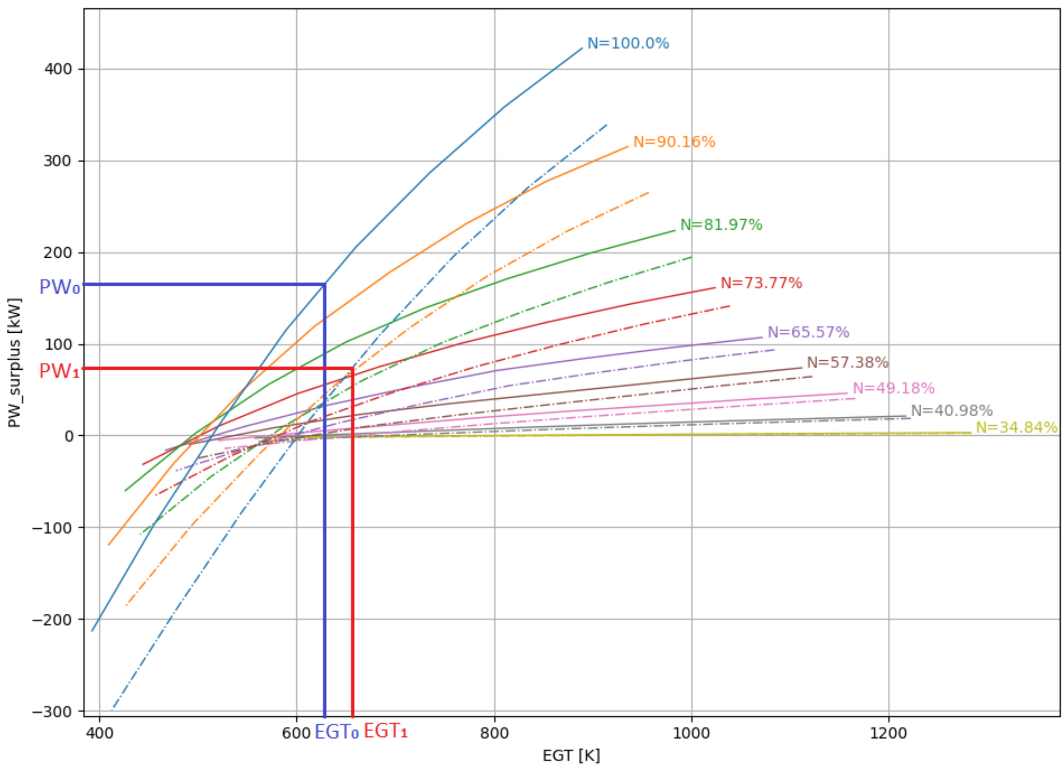


Figure 4.6: Surplus power PW_surplus of a healthy (solid line) and deteriorated (dashed line) APU

With the relative power contribution of each component known, we will be able to isolate the most likely cause for the aborted start.

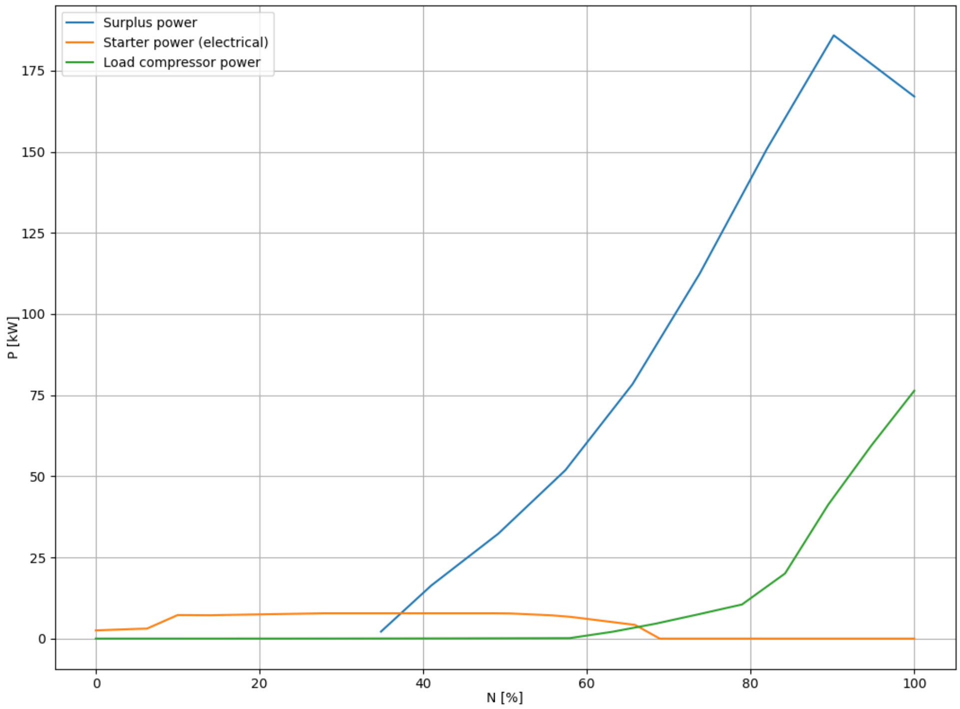


Figure 4.7: Power levels of gas turbine (surplus power) , starter-generator and load compressor at different core speeds; steady-state points

While this approach will not give accurate estimates on the actual values for power and temperature, it can be used to see the reduction in power caused by turbine and/or compressor deterioration.

Once the power drop is known, the delay in start time can be calculated with

$$t_{start,healthy} = I \int_{0\%}^{100\%} \frac{1}{Q_{st} + Q_{surplus} - Q_{lc}} d\omega = I \int_{0\%}^{100\%} \frac{1}{Q_{tot,healthy}} d\omega$$

$$t_n = t_{n,healthy} \frac{Q_{tot,n,healthy}}{Q_{tot,n}} = t_{n,healthy} \frac{P_{tot,n,healthy}}{P_{tot,n}}$$

$$t_{start} = \sum t_n \quad t_n \text{ is the time interval to accelerate from } N_n \text{ to } N_{n+1} \text{ shaft speed} \tag{4.2}$$

$$H_{st} = \frac{P_{st}}{P_{st,healthy}}$$

The reference (or healthy) state will be set as the first cycle after APU overhaul.

4.3. Condition Monitoring of Other LRUs

The other LRUs for which condition monitoring rules will be developed are the oil cooler, temperature control valve, bleed air valve, surge control valve and IGV actuator. Because of the limited number of parameters measured on-wing, undetectable degradation or lower failure rates, the rest of the LRUs listed in section 3.3 will not be further investigated.

4.3.1. Surge Control Valve

The purpose of the SCV is to prevent stall in the load compressor during operation. Using inlet temperature $T2$, the IGV position, the total and dynamic pressure PT and DP, the ECU calculates the surge margin and bleed flow. During APU start, the surge control valve is held fully open, while in MES, it is fully closed. A deviation from the expected position could indicate a malfunction of the SCV, but it could also be caused by a flow sensor error or the bleed air valve not being able to open. In order to isolate the fault, we need to consider the following:

- If the SCV is not fully closed (90°) during MES, this could indicate a stuck bleed air valve
- If the SCV is not fully open (10°) during APU start, this could indicate a faulty SCV

4.3.2. IGV Actuator

The actuator changes the angle of the IGVs from 15° to 90°. The ECU determines their position depending on inlet conditions, load demand and APU mode.

- During APU start, the IGVs are held closed at 15° up until 60% shaft speed, then opened at 22°
- During MES, the maximum position of the IGVs is from 68° at -54 $°C$ to 90° at 32 $°C$

Deviations from these positions could indicate a faulty actuator.

4.3.3. Oil Cooler

Clogging with dirt/dust of the cooling fins of the oil cooler will gradually increase the oil temperature with each cycle. Since MES is the highest loading mode, the rise in oil temperature will be most noticeable there. Normal values for T_{oil} are typically below 90 $°C$, so the health of the oil cooler can be expressed as

$$H_{cooler} = \frac{T_{oil,healthy}}{T_{oil}}$$

An oil leak will increase the oil consumption, however this parameter is not measured on the 131-9B.

4.3.4. Temperature Control Valve

The other possible reason for increased oil temperature is malfunctioning of the temperature control valve. If it is stuck in the open position, a large step increase in the temperature will be observed during MES, possibly leading to a protective shutdown. As stated previously, the normal oil temperature is around 90 $°C$. If the TCV is stuck in the open position, the increase in temperature could be as high as 50 $°C$.

A health parameter cannot be formulated for this LRU, but faults can be detected when the temperatures increases suddenly.

4.3.5. Bleed Air Valve

The bleed air valve regulates the amount of bleed air flow to the aircraft (used either for air conditioning or starting the main engines). As mentioned above, if the BAV cannot open fully, it would trigger an opening of the SCV during MES. Provided the flow sensors are accurate, an opening of the SCV indicates a BAV fault.

The BAV position can be estimated based on the bleed flow and IGV and SCV position. If the SCV opens during MES, this would indicate that the BAV cannot open enough.

5

Results and Discussions

In this chapter, we will discuss the results of the gas path model used to diagnose the starter-generator. Additionally, patterns in the engine parameters will be linked to degrading/faulty LRUs.

5.1. Starter-Generator Performance

Using the procedure described in section 4.2, the EGTs measured in the test cell are used to determine the fuel flow needed by the model, which will be the same for a healthy and deteriorated state. The decrease in surplus power can then be obtained by applying the desired deterioration factor to the model. The effect of degradation of different components on surplus power and EGT is plotted in Figure 5.1.

The results of the steady-state simulation of the start sequence of the APU are shown below. By sweeping through different speeds and EGT values and matching them to the test cell results, the fuel flow and compressor discharge pressure can be used to validate the model, which in turn calculates the surplus power. In order to achieve a successful start, the net power has to be positive. Therefore, if the surplus power is close to or below zero, it is the starter that has to provide enough power to accelerate the shaft. As can be expected, the turbine provides virtually no power in the low speed range. So it is up until 30% shaft speed that the starter motor is the dominant term in the power balance equation. Around the 35% speed mark is where the powers of the turbine, compressor and starter are the same order of magnitude. The contribution of the different components to the power balance is shown in Figure 4.7.

At speeds up to around 30%, the starter-generator contributes the most to the acceleration, after which the power levels of the turbine and compressor largely exceed the power of the starter-generator. The next step is to investigate how much delay will be caused in the start time due to deterioration of core components and starter power.

Assuming only the starter provides power at shaft speeds below 30%, we can calculate the time delay caused by a 20% reduction in starter power.

$$P_{st} = Q_{st}\omega = I\alpha\omega$$

$$\alpha = \frac{Q_{st}}{I}$$

$$t_{0-30,healthy} = \int_{0\%}^{30\%} \frac{1}{\alpha}\, d\omega = I\int_{0\%}^{30\%} \frac{1}{Q_{st,healthy}}\, d\omega$$

$$t_{0-30} = I\int_{0\%}^{30\%} \frac{1}{(1-0.2)Q_{st,healthy}}\, d\omega = \frac{t_{0-30,healthy}}{0.8} = 1.25t_{0-30,healthy} \quad (5.1)$$

Therefore, the time to accelerate to 30% is inversely proportional to the starter power and the starter health can be expressed as:

$$H_{st} = \frac{P_{st}}{P_{st,healthy}} = \frac{t_{0-30,healthy}}{t_{0-30}}$$

The issue here is that the time to reach 30% speed is not recorded onboard the aircraft. Not knowing the speed profile during the start, we need to determine if a delay in the start time is caused by core deterioration or starter deterioration (or a combination of both).

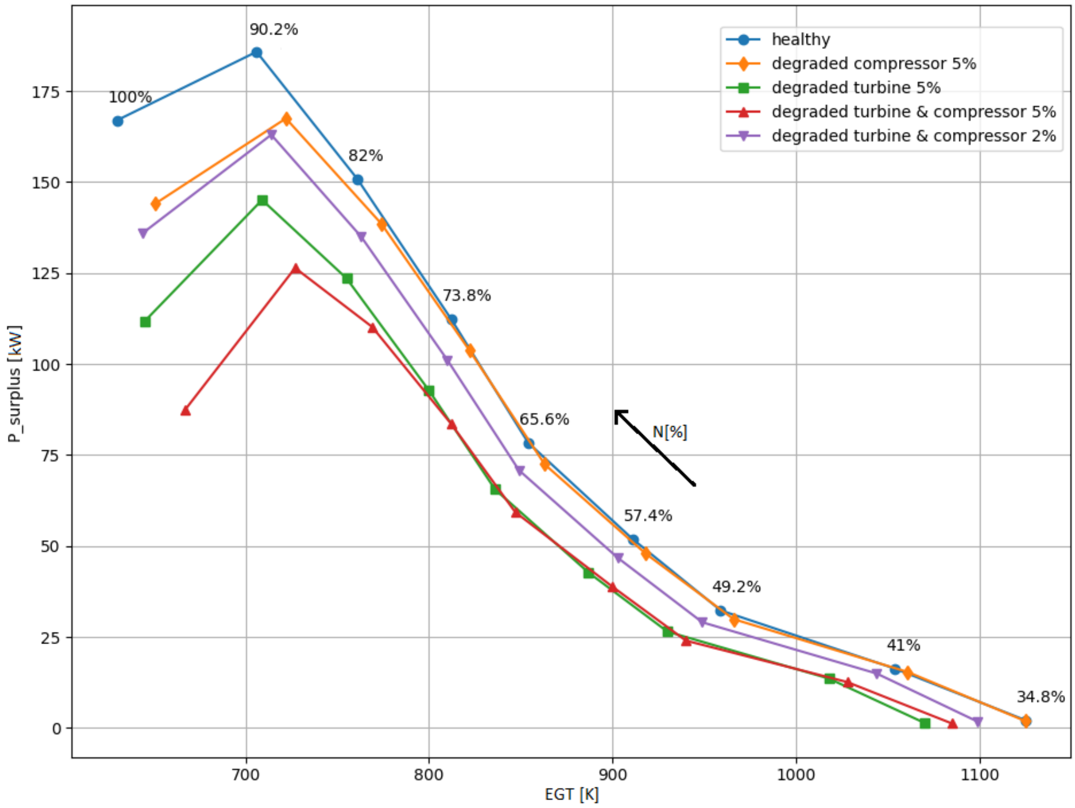
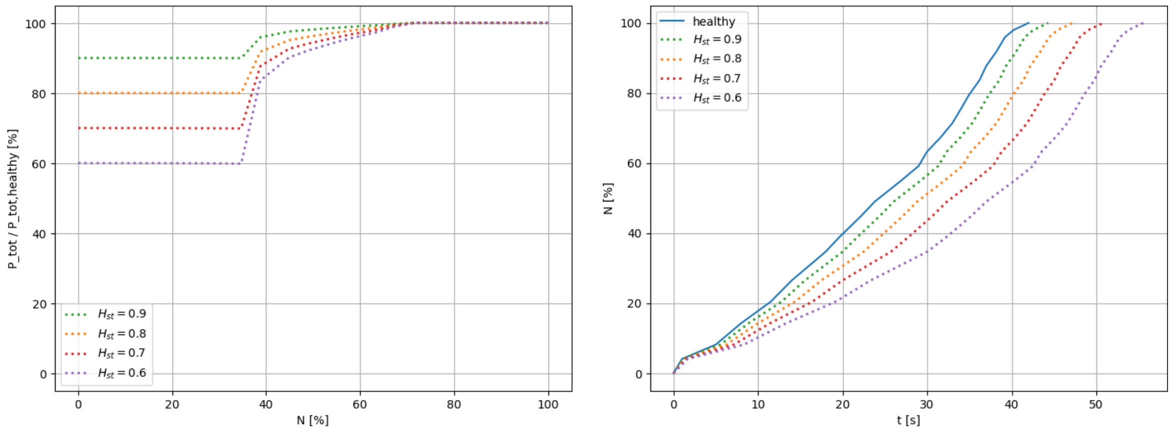


Figure 5.1: Change in surplus power and EGT caused by core degradation

We can also investigate what the influence of deteriorating core components is to the starting times. With the help of the GSP model, we know how much the power of each component will change when it degrades.

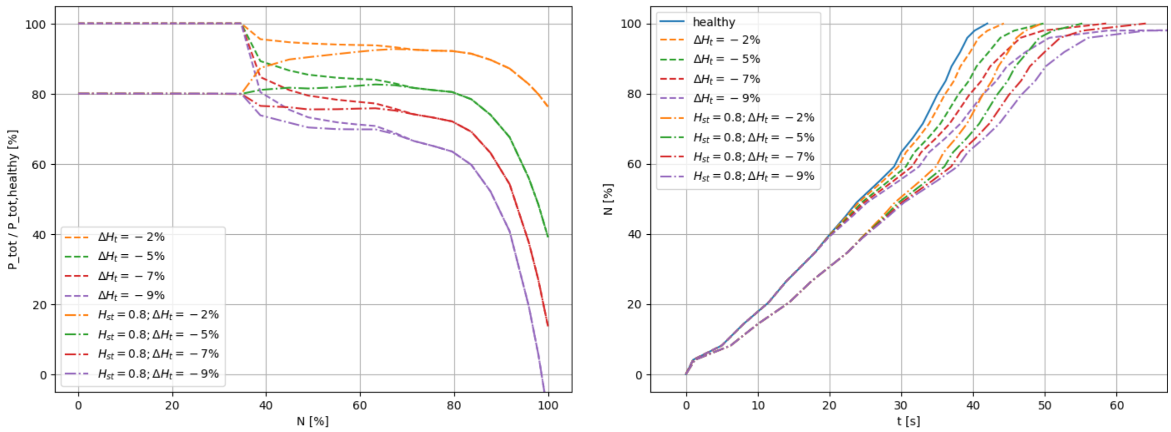
In Figure 5.2a, 5.3a, 5.4a and 5.5a, we have the total power of the APU relative to the healthy state. Computing the start profile is then done using Equation 4.2 (the results are plotted in Figure 5.2b, 5.3b, 5.4b and 5.5b). In these graphs we clearly see two distinct regions where either starter degradation or core degradation dominates. The start times (time to reach 95% shaft speed) are summarized in Table 5.1.



(a) Total power during APU start with degraded starter-generator relative to the healthy engine

(b) Speed profile of the APU start with a degraded starter-generator

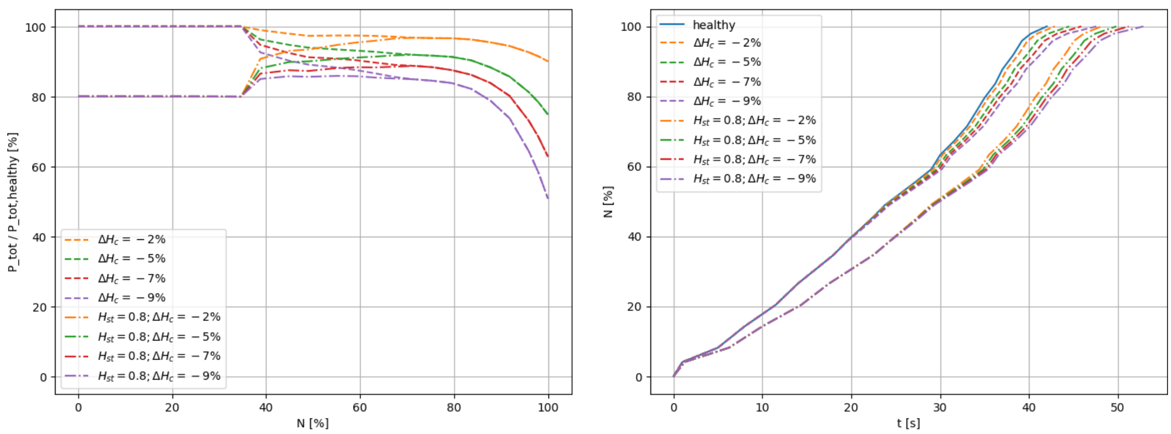
Figure 5.2: Influence of starter-generator health H_{st} on the APU start



(a) Total power during APU start with degraded turbine relative to the healthy engine

(b) Speed profile of the APU start with a degraded turbine

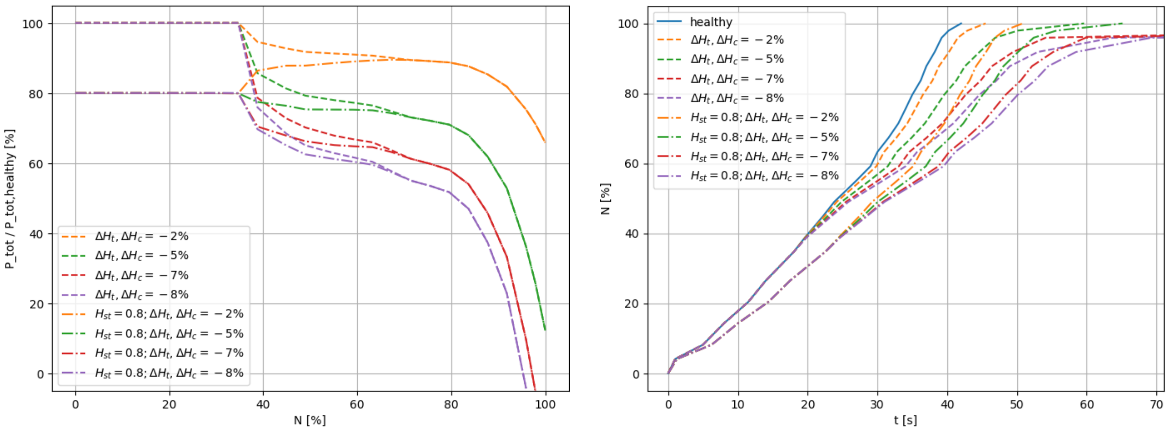
Figure 5.3: Influence of turbine deterioration ΔH_t on the APU start



(a) Total power during APU start with degraded compressor relative to the healthy engine

(b) Speed profile of the APU start with a degraded compressor

Figure 5.4: Influence of compressor deterioration ΔH_c on the APU start



(a) Total power during APU start with degraded compressor and turbine relative to the healthy engine

(b) Speed profile of the APU start with degraded compressor and turbine

Figure 5.5: Combined influence of compressor and turbine deterioration (ΔH_c, ΔH_t) on the APU start

Table 5.1: Start delay Δt_{start} in seconds of APU with different degraded components; $t_{start,healthy} = 38.97$ s

		$H_{st} = 1$	$H_{st} = 0.8$	$H_{st} = 0.6$
$\Delta H_t, \Delta H_c$	-0%	0	5.21	13.59
ΔH_t	-2%	1.53	6.82	15.2
	-5%	4.46	9.87	18.27
	-7%	7.15	12.67	21.06
	-9%	10.89	16.3	24.93
ΔH_c	-2%	0.61	5.86	14.23
	-5%	1.67	6.96	15.34
	-7%	2.46	7.78	16.17
	-9%	3.36	8.64	17.1
$\Delta H_t, \Delta H_c$	-2%	2.26	7.57	15.96
	-5%	7.4	12.91	21.3
	-7%	14.09	19.83	28.19
	-8%	22.37	27.86	36.58

Assuming that turbine deterioration is the dominant mode of deterioration, we can see that the start delay can be split into two parts, delay caused by the starter and delay caused by the turbine (which are quasi-independent):

$$t_{start} - t_{start,healthy} = \Delta t_{start} = \Delta t_{start,st} + \Delta t_{start,t}$$

We know that turbine degradation will increase EGT in other operating modes. We can simulate the degraded engine in different operating modes (e.g. MES and idle) to determine how much the EGT increases when the compressor and/or turbine deteriorate. Figure 5.6 and 5.7 show a very linear relation between EGT and deterioration factors.

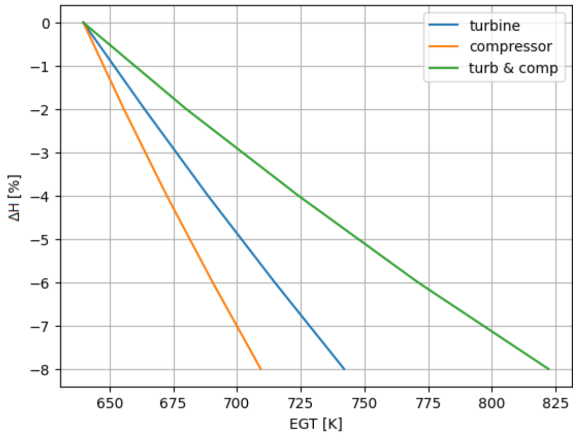


Figure 5.6: Core deterioration as a function of EGT in idle operation

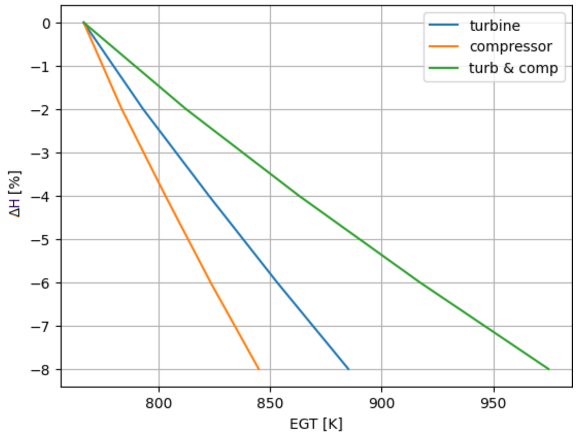


Figure 5.7: Core deterioration as a function of EGT in MES mode

Based on the start times listed in Table 5.1 and the correlation between EGT and turbine deterioration observed in Figure 5.7, we can calculate the delay $\Delta t_{start,t} = f(EGT)$. We then have $\Delta t_{start,st} = t_{start} - t_{start,healthy} - \Delta t_{start,t}$. Finally, looking back at Figure 5.2, we also know how $\Delta t_{start,st}$ will relate to the starter-generator health H_{st}. The relation can be approximated by the function (comparison in Figure 5.8):

$$H_{st} = \frac{20}{20 + \Delta t_{start,st}}$$

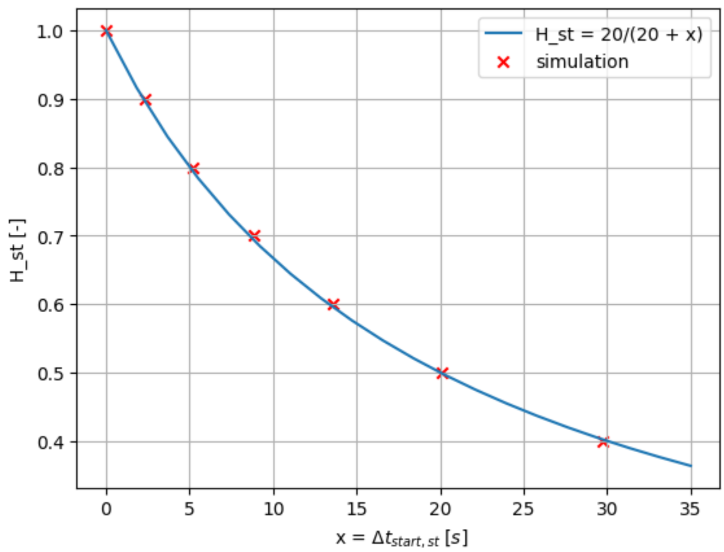


Figure 5.8: Starter health H_{st} as a function of start delay $\Delta t_{start,st}$

If we are to calculate the starter health of some real life APUs, we can observe their startup profile in Figure 5.9. These graphs show aborted start attempts because they failed to maintain 95% speed 60 seconds after startup was initiated. APUs 1 to 4 have a relatively healthy starter-generator (H_{st} is between 0.8 and 1), while APUs 5 to 9 have a much more degraded starter-generator (H_{st} is around 0.5 and below). We should note that the actual state of the APU components is unknown, as no inspection records were available.

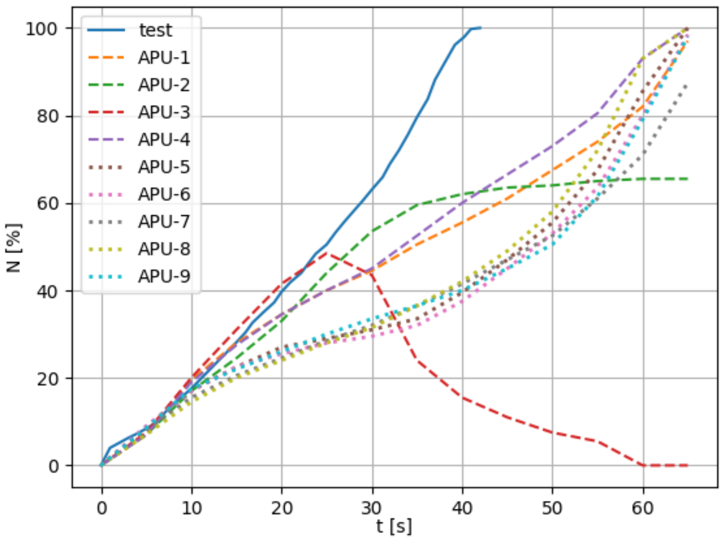


Figure 5.9: Test start (solid line) compared to on-wing aborted starts - due to starter degradation (dotted lines) or core degradation (dashed lines)

5.2. Empirical Rules for LRU Monitoring

Based on the trend of some parameters, some basic rules to monitor other LRUs will be presented.

5.2.1. Oil Cooler

Oil cooler clogging usually presents itself with a linear increase in oil temperature over time Figure 5.10. Setting a maximum allowed oil temperature, e.g. $140\ ^{\circ}C$, we can estimate how long the engine can operate before reaching it by extrapolating the gradient of the oil temperature over time.

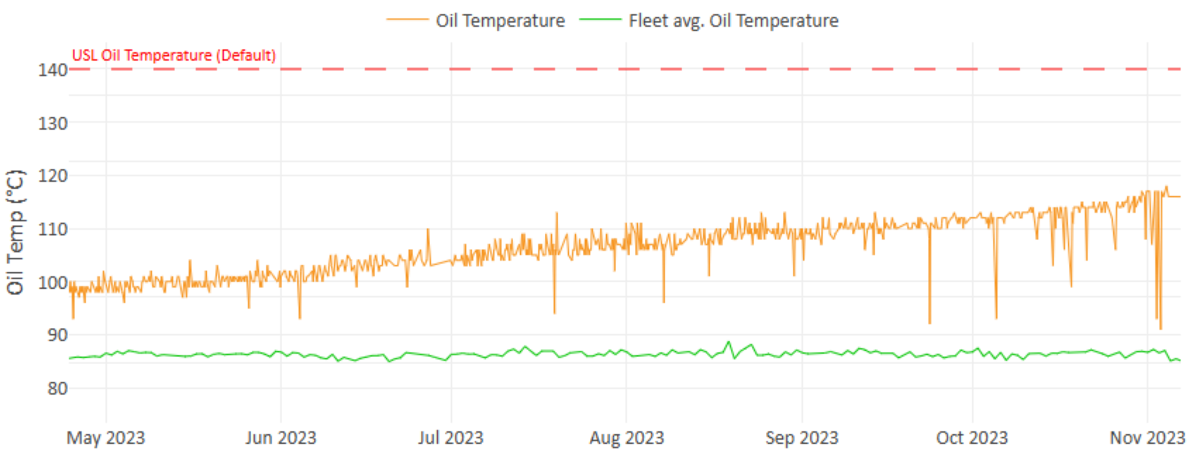


Figure 5.10: Oil temperature during MES; T_{oil} increases by approximately $2.5\ ^{\circ}C$ per month, we estimate the APU can operate for another 10 months before reaching $140\ ^{\circ}C$

When this linear increase in temperature is observed in other APUs, it is possible to estimate the remaining life of the oil cooler.

5.2.2. Temperature Control Valve

Considering the oil temperature again; if T_{oil} suddenly increases by 40 $^{\circ}C$ to 50 $^{\circ}C$, instead of the linear increase that would suggest clogging of the oil cooler, this would likely mean the TCV is stuck open, thus bypassing the oil cooler. Gradual deterioration of the TCV cannot be observed, instead a fault can be detected when this pattern in oil temperature is observed.

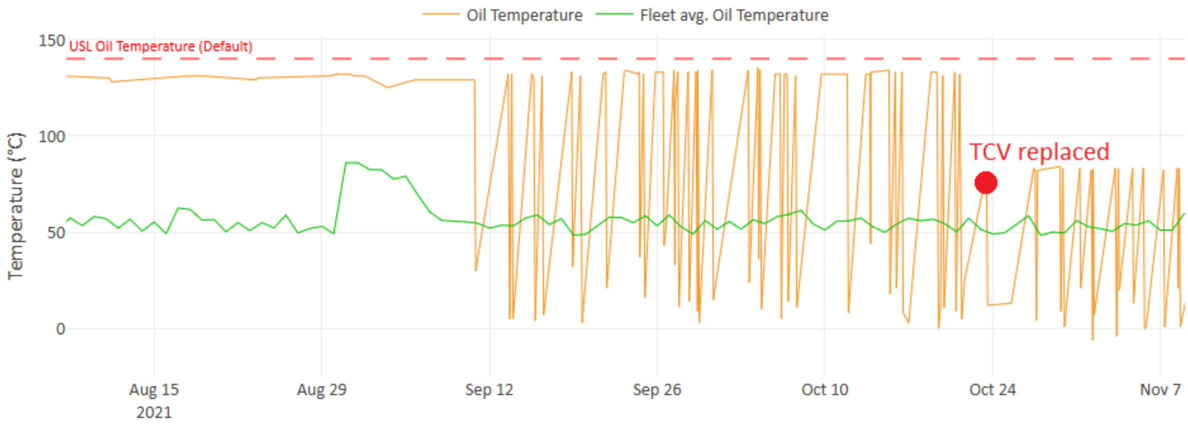


Figure 5.11: Oil temperature during MES (historic data does not go back further)

5.2.3. Bleed Air Valve

Like mentioned previously, the position of the bleed valve is not recorded. However, if it fails to open, the surge control valve will actuate when we do not expect it. An example can be seen below in Figure 5.12. In MES, the SCV should be set at 90°, however, something happens that causes it to open slightly by 10°. The same valve remains to its expected position of 11° when idling (see Figure 5.13), so we can determine that a BAV fault is the likely cause for this event.

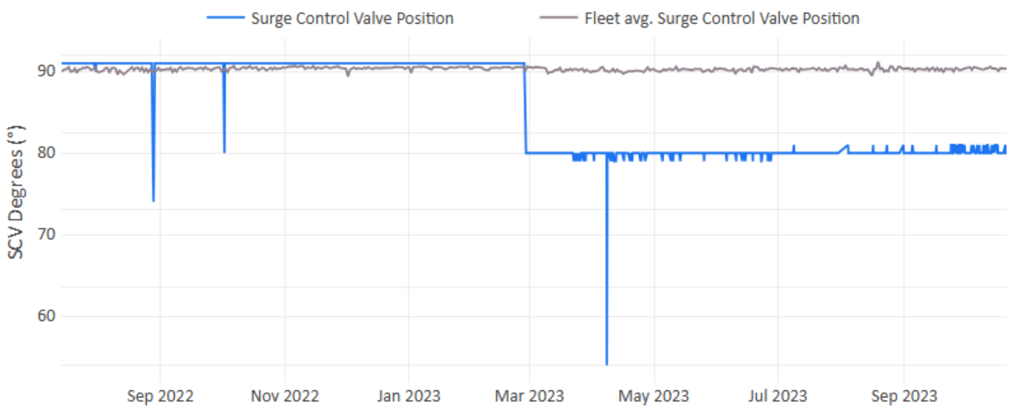


Figure 5.12: SCV position of an APU in MES mode

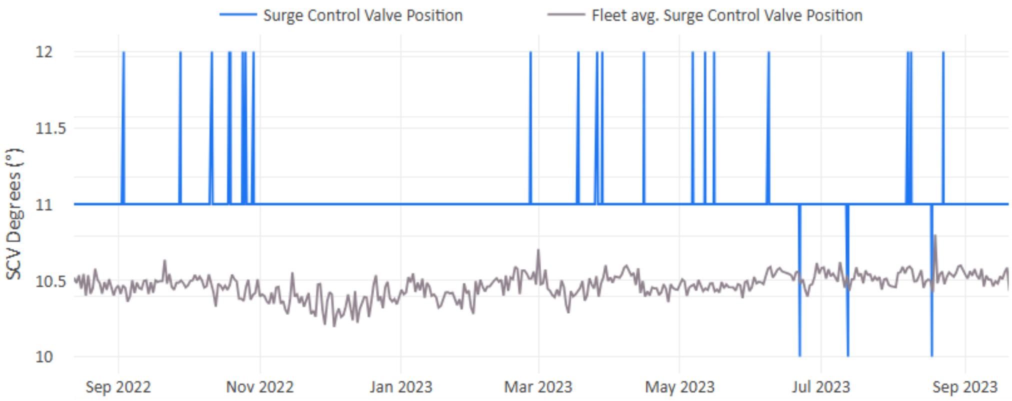


Figure 5.13: SCV position of the same APU in idle mode

6 Conclusions

Even with the limited engine measurements available, it is possible to monitor the health of some line replaceable units on the Honeywell 131-9B APU. Most significantly, the starter-generator, which has relatively high failure rate and repair costs, can be monitored using only two parameters; the start time and EGT during MES. In cases where the EGT increases too much (by roughly $150\ ^{\circ}C$), the APU might be unable to start regardless of the condition of the starter-generator.

While some assumptions need to be made (such as core degradation is caused by the turbine, the decrease in efficiency is equal to the increase in mass flow), the resulting starter health parameter H_{st}, which is correlated to the mechanical power, can be used to create a better maintenance schedule. Another way to prevent failure of the starter-generator is by using the shutdown messages (specifically the clogged scavenge filter indication) to identify an increased risk of shorting.

Additionally, actuators whose positions are measured and recorded can easily be monitored for faults if they deviate from the control input.

The condition of the oil cooler and temperature control valve can also be monitored since they have a strong coupling with the oil temperature. Looking at the temperature evolution over time, we have two distinct events; gradual rise, which indicates clogging of the oil cooler, and sudden step increase, which indicates a faulty temperature control valve.

Finally, the bleed air valve can be indirectly monitored via the surge control valve position. If a consistent offset in SCV position is observed only during MES, the most likely cause is a faulty bleed air valve.

7
Recommendations

- To improve the confidence in the diagnostic rules and validate them, observing future failures of LRUs and the affected engine parameters is needed.
- A dynamic model will provide a more accurate image of the APU start. For that more technical data of the APU is required, such as shaft inertia and more accurate compressor and turbine maps (for example by using CFD).
- The Honeywell 131-9C, which is a very similar APU to the 9B, records the engine parameters continuously (meaning time series data is available as opposed to snapshots). Investigating them during operation may provide additional relations between faulty/deteriorated LRUs and affected parameters, which could also be relevant for other APU models.
- A big challenge in the current diagnostic capabilities is keeping record of all servicing tasks performed on a given APU. For consistency and better understanding of effect of individual LRU to APU performance, adding timestamps in Prognos when LRUs have been swapped/repaired would be an improvement.

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A

Thesis Assignment

Failure detection of Line Replaceable Units of Auxiliary Power Units

MSc Assignment for **George Rulev (#5079403)**, FPP, Aerospace Engineering, Delft University

Overview

The traditional maintenance for APUs (small gas turbine engines) is changing from prescribed maintenance intervals, or letting it fail, to condition based maintenance combined with prognostic capabilities. As the health/condition of the APU depends on the condition of the individual components, it is believed that changing line maintenance components (Line Replaceable Units) that deteriorate/fail will result in a better APU condition for prolonged usage.

Objectives and Goals

The aim of the thesis is to detect failed/deteriorating LRU performance (of a selected APU type, e.g. the Honeywell 131-9B) by means of smart use of the measurement data that is captured in our condition monitoring and predictive maintenance tool called Prognos for APU®. A literature study, a classification of LRU fail mechanisms, modelling of the APU in NLR's Gas turbine Simulation Program, GSP, and development of algorithms (possibly AI driven) is part of this study.

Background and Context

EPCOR BV is a company specialized in Maintenance, Repair, and Overhaul (MRO) services, primarily focusing on Auxiliary Power Units (APUs) and pneumatic components for large commercial aircraft. With over two decades of experience in airline MRO, EPCOR has developed substantial expertise in this field. The company holds seven APU licenses and has a notable record of having overhauled more than 2600 APUs, alongside monitoring over 1200 APUs. This level of activity highlights EPCOR's significant capacity and capability in the APU overhaul segment.

Expected Outcomes

The expected outcome is to create a proof of concept to determine the LRU condition from measured APU performance, usage and condition data.

Resources and Support Available

Microsoft cloud based solutions are available to get datasets for use in python driven solutions, or development of algorithms with the use of Microsoft PowerBI directly acting on the complete dataset. Support will be given by the EPCOR Product Owner Predictive Maintenance.

Gas turbine Simulation Program GSP 12 to analyse the relationship between LRU performance and measured APU performance and condition.

Report

Results of the work must be reported in English, with a copy of this assignment and an executive summary.

Start and coaching

The work will start 22 July 2024 and be performed in close collaboration with EPCOR BV

Professor,	Delft University supervisor,	Supervisor at EPCOR
Prof. dr. ir. P. Colonna	Dr. ir. W.P.J. Visser	O. Kogenhop M.Sc. B.Eng