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A Health Monitoring Modelling Case Study: Humidity Effects on Engine Deterioration Prediction

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Abstract. This work focuses on humidity effects of turbofan engines, in order to identify the magnitude of the error in operational conditions and the implications on maintenance decision support. More specifically, this paper employs a set of different methods, including semi-empirical corrections used in engine test beds, performance simulation models and analysis of historical data, in order to investigate the effects of humidity. We show that varying humidity can have a noticeable influence on the performance of the engine. These discrepancies cannot be currently quantified by health monitoring systems. Simulation and test bed correlations indicate a decrease of EGT of 0.35% per 1wt% of absolute humidity, which varies worldwide between 0 and 3wt%. Consequently, deviations in EGTM can be up to 1%, a figure which can be up to 12K for a modern civil turbofan. In practice, variations in ambient humidity have the potential to conceal possible deterioration in engine components. Following, the flight historical data were corresponded to historical humidity data. The two methods were identified to provide comparable results, indicating a higher EGTM for increasing ambient humidity. Overall, it was concluded that EGTM corrections for ambient humidity is an area of significant interest, especially for newer engine types where accurate diagnostics are of increasing importance.

1 Introduction

Engine health monitoring is a crucial function for aircraft operators and Maintenance, Repair and Overhaul (MRO) providers, for two main reasons: First, to secure a safe and reliable operation and second, to identify the maintenance needs of individual engines. Timely and efficient maintenance is becoming of greater importance for MRO companies, driven by competition, as a total of \$82 billion has been spent on MRO in 2019, of which approximately 41% corresponds to engine maintenance costs [1]. In addition, MRO costs represent around 10% of an airline's annual operational cost [2]. Under this frame, the accurate assessment of the condition of a large turbofan engine is paramount.

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It is known that the operational profile of aircraft has a distinctive signature in the deterioration modes of its components [3]. However, the exact mechanisms that link the operational environment with deterioration of aircraft parts are not considered in MRO programs as a standard input, a practice that can miscalculate the maintenance needs of assets. In more details, the scope of individual shop visits, or even long-term maintenance programmes is usually determined before the induction of actual engines and the necessary inspections that take place, and it is mainly based in standardised rules that take into account the accumulated flight hours and flight cycles [4]. This results in the underestimation of the influence of environmental factors that can have an adverse impact in the planned type of maintenance. This is also why some MRO projects are characterised by longer than planned lead times, excessive costs and unpredictability in materials.

The main key performance indicator of a gas turbine engine is the Hot Day Exhaust Gas Temperature Margin (EGTM). As EGTM we define the temperature difference between an averaged value of the exhaust gases and a redline that indicated an operational limit for the engine. The averaged gas value is influenced by the number of thermocouples in the annulus of the hot section of an engine, the presence of any hot streaks and other geometrical factors, which we assume that remain constant throughout its lifetime. Similarly, there is a number of different gas temperature values that can be considered as different operational limits, a topic which is out-of-scope for this paper.

Exceeding a gas temperature limit, which results in negative EGTM, means that an engine has reached its operational limits and some actions are needed on the operator's side [5]. This can be a simple washing [6], which removes particle contamination, associated with compressor fouling. (figure 1) However, at the same time engines deteriorate mechanically at a slower pace, reaching eventually a limit where their overall thermal efficiency cannot be improved with washing. In an MRO context, the EGTM acts as a measure of the overall thermal efficiency of engines, since mechanically deteriorated components along the gas path are characterised by reduced isentropic efficiencies and increasing gas temperatures during the accumulation of flight cycles [7].

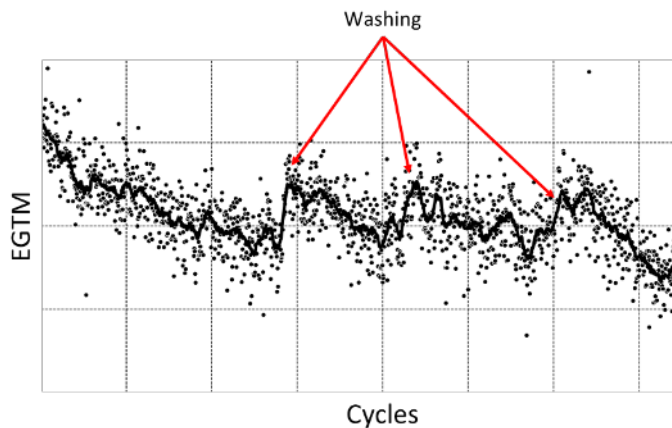


Figure 1: Engine deterioration and Washing

An important question to ask is how accurate is the measurement of EGT and what is the influence of the atmospheric parameters on it. As the composition of air varies with ambient conditions, the reported EGTM might also be partially inaccurate with varying absolute humidity. The thermodynamic properties of air are a function of the proportion of water in it

and thus, the same engine will report different EGTM with varying humidity. A major point to make is that ambient humidity is not measured by modern aircraft and thus, they have no technical means to correct EGT for it. As a result of this technical shortcoming, the main research finding that will be presented in this work can be stated as follows:

In this paper, a computational framework is proposed that augments engine diagnostics by correcting on-wing reported EGTM for ambient humidity variations.

2 Modelling of Humidity Effects

2.1 Background

In order to understand the magnitude of the influence that varying ambient humidity has in EGTM, we need to start by identifying the boundaries of the problem. As a starting point, we need to state that humidity can be measured as absolute or relative. Absolute humidity is the amount of water vapor present in one cubic meter, measured in grams per kilogram of air (g/kg^3). Relative humidity is defined as the ratio of the actual amount of water vapor to the amount of water vapor at saturation at a given pressure and temperature. Since hotter air can contain more water, we can observe that for the same relative humidity, a hotter environment implies a higher absolute humidity, a higher effect in the thermodynamic properties of air and thus, a higher humidity effect in engine performance, in parallel with other performance effects due to the operating environment.

After understanding the operational effect of humidity in engine diagnostics, one can be able to identify whether any operational rules need to be re-examined. The whole process is illustrated in figure 2.

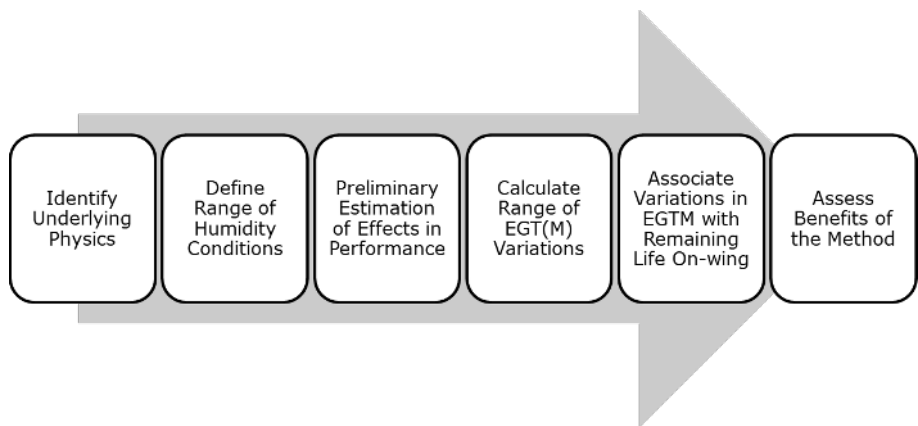


Figure 2: Problem methodology

2.2 A Simplified Analytical Model

In the following calculation, we try to identify the magnitude of the effect of humidity in two real cases, characterised by humidity levels at the two extremes of the spectrum. We used open literature yearly-averaged weather data for the airports of Singapore and Aswan, Egypt. The selection of the two locations was based on the fact that Singapore is very humid, while

Aswan is very dry. The yearly-averaged ambient temperature is similar, a fact that can isolate the effect of humidity. The data used to perform this calculation follow in Table 1, while the last row contains the calculated absolute humidity

Table 1. Meteorological Data for Singapore and Aswan, Egypt.

	Singapore	Aswan
Yearly-averaged relative humidity	83.5%	26.2%
Yearly-averaged ambient temperature	27.5°C	25.9°C
Yearly-averaged ambient pressure	101.325 kPa	99.099 kPa
Average air density	1,1629 kg / m ³	1,1534 kg / m ³
Yearly-averaged absolute humidity	2.0 wt%	0.5 wt%

An observation we can make in table 1 is that for similar averaged ambient temperature, the absolute humidity can fluctuate by 1.5 wt%. In extreme weather conditions that can occur sporadically, this discrepancy can be even higher. In literature, Bird and Grabe [8] came up with the following empirical correlation regarding the effect of humidity in Turbine Inlet or Outlet temperature in gas turbine engines.

$$C_T = 1 - 0.0845 H - 0.119 H^2 \tag{1}$$

The result of this calculation for Singapore is C_T = 0.99799, while for Aswan is C_T = 0.99957. By assuming an EGT of 870°C (1143K) in a dry air environment (0% relative humidity), the indicated EGT will be as follows:

Singapore *EGT = 1140.8K = 867.7°C*

Aswan *EGT = 1142.7K = 869.5°C*

Therefore, we observe a discrepancy in the reported EGT or EGTM by ΔT = 1.8°C, which can be reported for the exact same engine, with the exact same level of degradation and deterioration in its hardware. In order to understand whether this deviation is significant, we will make the following calculation, starting with the question “How much engine life corresponds to 1.8°C of EGTM?”

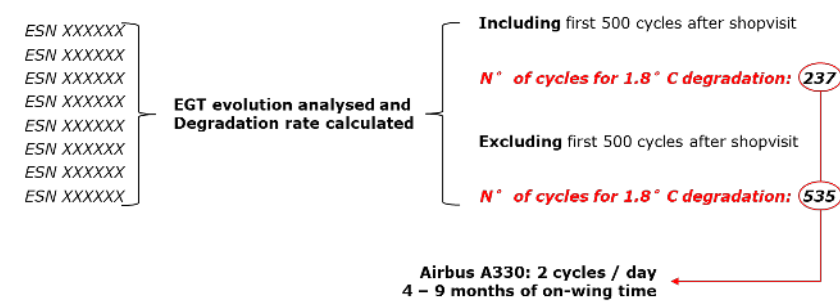


Figure 3: Rate of deterioration for a pool of 8 large turbofan engines

We put together a group of eight large gas turbine engines which operate for a large airline. The engines were selected to represent different rates of degradation, as individual engines behave in a different way in this domain. It is important to mention here that a typical gas turbine deteriorates faster right after a shop visit, while the slope of degradation becomes less steep after an amount of cycles is accumulated. For the sake of this study, we examined two time windows, the first with the first 500 cycles after a shop visit included and the second with the first 500 cycles excluded. As illustrated in figure 3, the 1.8°C of discrepancy in EGTM between the two locations corresponds to approximately 237 cycles for this specific pool of engines in the first time window, where deterioration is faster, while it corresponds to approximately 535 cycles in the second time window, where deterioration is slower. We can tell empirically that this number of cycles corresponds to roughly 4 to 9 months of on-wing time for a wide body aircraft, so systematic misreporting of EGTM can make a shop visit premature or overdue, depending on the initial assumption for ambient humidity for an engine manufacturer. In other words, if an engine manufacturer assumes that the environment is dry (e.g. equal to 0 wt% humidity), then taking into account the effects of ambient humidity will make a shop visit overdue, while an assumption of high humidity (e.g. 90 wt%) for an engine operating in dry environments, it will make a shop visit premature.

2.3 Data Analysis

As aircraft are not equipped with humidity sensors, the solution to acquire data for this project came from the domain of Flight Operations. Airline pilots are briefed about the weather via some special messages that contain meteorological information, known as METAR [9]. A METAR weather report includes information about the airport and time, the temperature, dew point and the altimeter setting (figure 4), which denotes the ambient pressure. With the ambient pressure and temperature known, the dew point can be transformed into relative humidity by converting dew point temperature and ambient temperature into water vapour pressures.

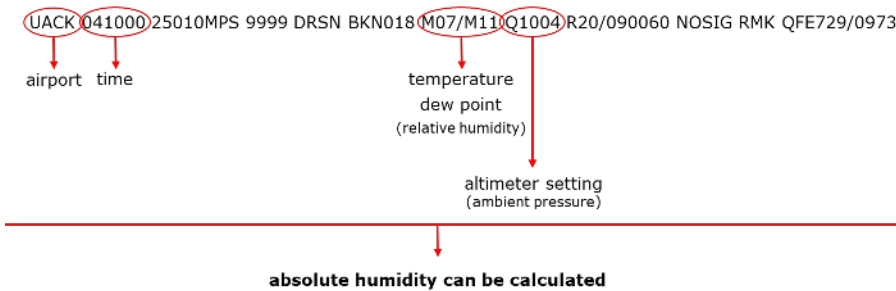


Figure 4: METAR message explanation

As METAR weather reports have a widespread use in aviation, they can be used as a substitute for the lack of humidity sensors onboard aircraft (figure 5). It is important to mention that the exhaust gases of engines have their maximum value during takeoff, where maximum thrust is required and ambient temperature is at its highest level. As a result, METAR messages are ideal for this type of calculation, as they always refer to specific airports. However, as airports can cover large land areas, there might be local variations in the meteorological conditions that are not taken into consideration.

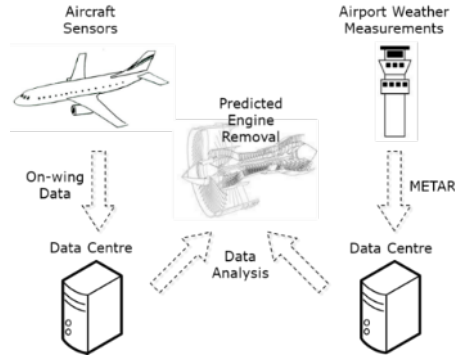


Figure 5: Data sources for engine removal prediction

3 Results

In this study, we used linear regression, in order to correct the effects of ambient humidity for anonymised on-wing operational data of two types of large turbofan civil engines (Engine type 1 and Engine type 2). For engine operators and MRO providers, such simplified correlations are preferable, as they can be easily implemented in operational environments. Two different tools were used to examine the impact of humidity across the whole operational range of these engine types: The first is the correlations used in experimental rigs, known as test beds, where engines are tested after every shop visit. As mentioned before, aircraft are not equipped with humidity sensors, however test beds are. As a result, engine manufacturers and maintenance providers come up with different correlations that account for different effects that take place during these tests, including the presence of ambient humidity [10]. The second method is the use of engine performance simulation tools, one of which is GSP (Gas turbine Simulation Program) [11], developed by the Dutch Aerospace Center (NLR). It is important to mention that the original values of EGT were measured by the engine manufacturer with the assumption of 0 wt% humidity, which means that the correction for real conditions of humidity will result in a reduced EGT.

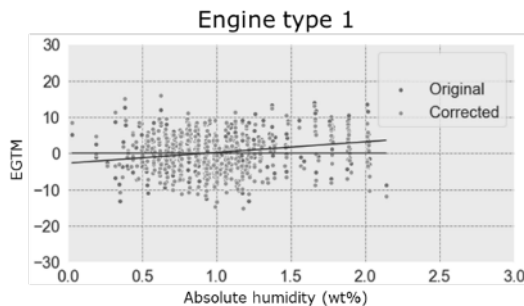


Figure 6: EGT humidity correction for on-wing data of Engine type 1

Both the test bed correlation and the calculation made by GSP indicate that for Engine type 1 every additional degree of weight percent absolute humidity results in a correction slope of 0.35% EGT. This value is higher than the one calculated in section 2.2, but it can be justified by the different performance characteristics of different engine types. However, both

studies provide results that are considered non-negligible and can have a significant impact in the decision support processes regarding engine maintenance and failure prevention. Figure 6 presents the variation of EGTM for the original data and the corrected one for Engine type 1, based on the test bed and GSP correlation.

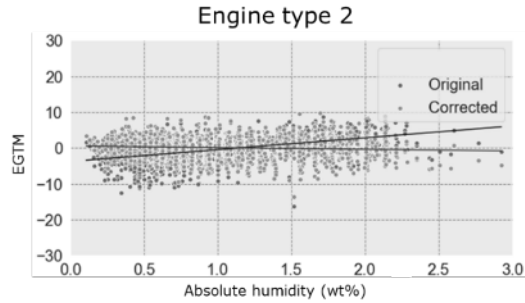


Figure 7: EGTM humidity correction for on-wing data of Engine type 2

Similarly, for Engine type 2 we see a similar behaviour when it comes to humidity correction, as illustrated in figure 7. Here, the correction slope is calculated at 0.33% EGT per wt%, a slightly lower value, which derives from both the test cell and GSP results. The original EGTM measurements are characterized by a lower scatter and a higher variation of humidity compared to Engine type 1. This can be attributed to the following two reasons: First, the two types have different cycle design characteristics, which allow for different variance in EGTM. Second, a wider range of EGTM values can also be observed due the operational profile of this engine type.

When applying these corrections to the operational history of a single example of each engine type, we come up with the results in figure 8, which illustrate the snapshot takeoff EGTM against a large number of flight cycles. It is important to mention that the cycles and EGT values were omitted for confidentiality reasons. The impact of humidity in the original EGTM is visible.

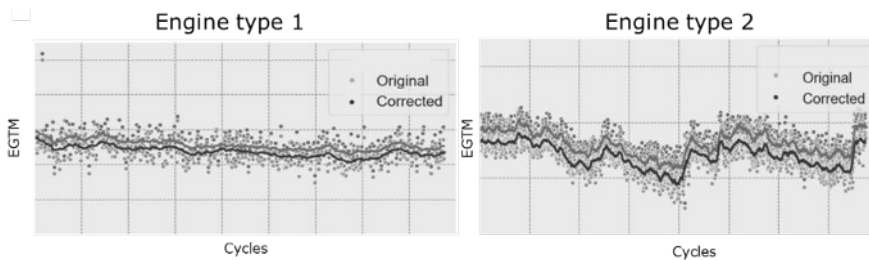


Figure 8: Corrected EGTM for a large number of flight cycles (Engine types 1 and 2)

4 Conclusions

This paper investigates the way ambient humidity effects are handled in operational aviation environments. It is known that aircraft do not have humidity sensors and therefore do not take into considerations the effects of humidity in the main engine health metric, the EGTM. As a result, EGTM might be misreported, depending on engine type, condition and its operating environment. We proved that this effect can be significant from an operational

standpoint and it can trigger corrective actions that can extend or reduce the on-wing time of engines, in order to prevent possible mechanical events, or even failure. The authors suggest the introduction of humidity information based on the METAR weather reports at airports, which are widely available in the aviation domain. There are different ways to correct the reported EGTM with the effects of humidity. Linear regression is accurate enough to capture these effects, but also simple enough to be implemented in complex operational environments where transparency and explainability are important for its operational support. The results obtained indicate an adverse effect on EGTM for the two engine types investigated, as a result of the practice of the engine manufacturer to assume that ambient humidity is 0 wt%. In the opposite scenario where humidity is always assumed to be high, the correction for humidity would provide a positive effect in EGTM. Overall, this work presents a framework that enables the augmentation of engine diagnostics with almost real-time weather data. This framework can have an important impact on operational decision support in aviation environments, where the effects of humidity are systematically neglected.

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