Engine condition monitoring on small single engine turboprop

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Abstract

Purpose – This study aims to focus on verifying the possibility of monitoring the condition of a turboprop engine using data recorded by on-board avionics Garmin G1000. This approach has potential benefits for operators without the need to invest in specialised equipment. The main focus was on the inter-turbine temperature (ITT). An unexpected increase in temperature above the usual value may indicate an issue with the engine. The problem lies in the detection of small deviations when the absolute value of the ITT is affected by several external variables.

Design/methodology/approach – The ITT is monitored by engine sensors and stored by avionics 1× per second onto an SD card. This process generates large amount of data that needs to be processed. Therefore, an algorithm was created to detect the steady states of the engine parameters. The ITT value also depends on the flight parameters and surrounding environment. As a solution to these effects, the division of data into clusters that represent the usual flight profiles was tested. This ensures a comparison at comparable ambient pressures. The dominant environmental influence then remain at the ambient air temperature (OAT). Three OAT compensation methods were tested in this study. Compensation for the standard atmosphere, compensation for the standard temperature of the given flight level and compensation for the speed of the generator, where the regression analysis proved the dependence between the ambient temperature and the speed of the generator.

Findings – The influence of ambient temperature on the corrected ITT values is noticeable. The best method for correcting the OAT appears to be the use of compensation through the revolutions of the compressor turbine NG. The speed of the generator depends on several parameters, and can refine the corrected ITT value. During the long-term follow-up, the ITT differences (delta values) were within the expected range. The tested data did not include the behaviour of the engine with a malfunction or other damage that would clearly verify this approach. Therefore, the engine monitoring will continue.

Practical implications – This study presents a possible approach to turbine engine condition monitoring using limited on board avionic data. These findings can support the development of an engine condition monitoring system with automatic abnormality detection and low operating costs.

Originality/value – This article represent a practical description of problems in monitoring the condition of a turboprop engine in an aircraft with variable flight profiles. The authors are not aware of a similar method that uses monitoring of engine parameters at defined flight levels. Described findings should limit the influence of ambient air pressure on engine parameters.

Keywords Turboprop engine, Trend monitoring, Engine health monitoring, Inter-turbine temperature

Paper type Research paper

Nomenclature

Symbols

Definitions, acronyms and abbreviations

ECM = Engine condition monitoring;
EGT = Exhaust gas temperature;
FC = Fuel consumption;
ISA = International standard atmosphere;
ITT = Inter-turbine temperature;
ΔITT = Difference of inter-turbine temperature from base point;
GA = General aviation;
GPA = Gas path analysis;
NG = Gas generator turbine speed;
OAT = Out air temperature; and
TRQ = Engine output torque.

Introduction

An increasing number of small airplanes, such as Cessna 208 Caravan, TBM 650, Pilatus PC-12 and others, are now equipped with modern turboprop engines. These airplanes

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Further work: Future research will focus on validating the proposed method on a worn or damaged engine.

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often operate on a wider variety of unpaved or less-maintained runways with lower surface quality than standard international airports. The engines of these airplanes may be endangered by excessive gas path wear or possible ingestion of foreign objects or dust. Such wear reduces engine life and increases fuel consumption (FC). Furthermore, higher thermal loads due to lower engine efficiency can increase the risk of critical engine parts failure. Therefore, engine condition monitoring (ECM) systems have been used for a long time. The deployment of such programmes benefits both operators and engine producers. Producers of turbine engines and airplanes offer their customers comprehensive and advanced ECM programmes. For various reasons, these programmes may not suit all proprietors or operators; hence, several alternative service suppliers have entered this market. To illustrate the importance of this area of expertise, the ECMs market is currently around US$249.37m, and the expected market growth in this area is 5% according to the Business Wire Company.

The vast majority of these commercial ECMs have been developed for large airlines that have relatively similar flight profiles within given aircraft categories and operate large numbers of the same power plant type. In comparison, general aviation (GA) faces a number of challenges that need to be addressed when creating a feasible ECM programme. This is primarily about evaluating the operational data of private turboprop aircraft, which are defined by a great variety of flight profiles depending on the *ad hoc* needs of customers and their activities, resulting in difficulty in defining comparable operational conditions. In addition to that, the GA airplanes are equipped with a minimum of special sensors useable for ECM, mainly due to space or cost savings. As a consequence, the specificities of small operators just mentioned can then lead to false indications of an arising problem or their complete ignorance. On the other hand, digital instruments are able to record and store a lot of information about the flight and engine parameters. Such large volumes of data then require automated processing as the labour costs of small operators can eliminate the potential for savings. Arrival of new small turboprop engines such as the TP-R90 from Tubotech Company for two-seater sports airplanes opens up new opportunities for ECM applications in this specific operation.

The motivation for this research is to offer an affordable and user friendly ECM system for private operators. For economic success, the operational savings and benefits must be greater than the costs of operating the ECM system. Therefore, it is necessary to ensure maximum automated data processing, limit the need for expensive additional sensors and provide a reliable warning in case of deviations.

In this paper, the possibilities of harvesting data from the Garmin, especially the G1000 avionics system, to monitor engine health trends for a private operator of a single-engine aircraft operated on various flight missions are tested. As part of this research, a customer-oriented ECM system with automated data processing and analysis was designed and built with the focus on high reliability of pending problem indications for various flight profiles that represent typical mode of operation. The merit of this paper is to cover implementation of the ECM programme under real GA operation conditions and to discuss possible solutions to these specific problems within a niche area that has minor coverage in professional discussions.

Problem description

The paper focuses on the area of monitoring engine performance through assessment of parameters indicating the level of engine wear. Engine health can be evaluated using different approaches which are described in many sources (Urban, 1997; Tumer and Bajwa, 1999; Babbar, 2009; Daroogheh, 2012; Zhang and Wang, 2012; Kong, 2014; Volponi, 2014; Simon and Rinehart, 2016; Kiyak, 2018; Cui, 2021). A number of methods focus on identifying the gas path condition. The gas path of the turbine engine is affected by a number of negative influences such as the accumulation of dirt, damage by foreign objects and worn seals. The aim of gas path analysis (GPA) methods is to monitor the course of wear over time and detect possible damage. A number of GPA methods have been developed over time and are covered by Loboda (2007), Yildirim and Kurt (2018) an Li (2020). The law of normal and gradual degradation of engine power is known and established and so are the values of the monitored parameters also predictable, practically throughout the life of the engine (Yepifanov and Loboda, 2003; Lu, 2019; Leser Patrick *et al.*, 2020). The choice of assessment methods is determined by the application area of the engine and the economic costs of implementing and maintaining the method. Ideally, the chosen method will help reduce the cost of operation and maintenance, and these savings are greater than the cost of monitoring, which generates profit. Expert sources are dominated by GPA methods developed for stationary gas turbines that have a relatively stable operating point (Yepifanov and Loboda, 2003; Putz, 2017; Koskoletos, 2018; Fentaye, 2019; Listou Ellefsen *et al.*, 2019; Pérez-Ruiz, 2021). In our case, the operating point is strongly influenced by the flight parameters, and in addition, a limited number of operating parameters are available. The following key parameters related to engine power are typically monitored by any avionic system:

- output shaft torque (TRQ) – provides engine performance information;
- fuel consumption (FC) – which in combination with the engine torque indicates efficiency of the energy conversion;
- generator turbine speed (NG) – which is related to mass flow; and
- inter-turbine temperature (ITT) indicating thermal load of the engine.

The process of data filtering and pre-processing is the subject of our article. From the measured data, it is necessary to define stable operating points that are comparable. An important element for condition analysis is to determine the deviation of a given parameter from the reference or base value, the so-called deltas. The base value is usually represented by the condition of a new or repaired engine. Trend analysis corresponds to the time evolution of given delta parameter. Depending on the parameter under analysis, its delta can be expressed in the same units as the parameter or as a dimensionless ratio as seen in the following equations for delta ΔITT example:

$$\Delta ITT = ITT_{\text{act stab point}} - ITT_{\text{base point}} [^\circ C] \qquad (1)$$

where:

ΔITT = deviation from the baseline value ITT (°C);
$ITT_{\text{act stab point}}$ = actual corrected value of ITT for define stable point (°C); and
$ITT_{\text{base point}}$ = defined value ITT for new engine (°C).

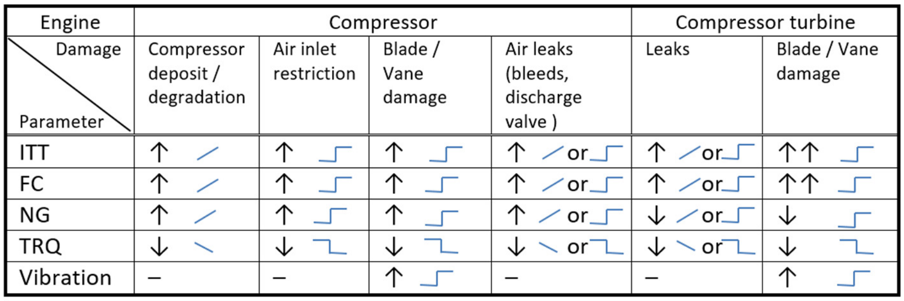
Other key engine parameters such as engine output torque (TRQ), NG and FC can be monitored using an analogous method. The mutual relationships among the parameters and the rate of change may indicate a potential problem. The possible modes of such transitions are indicated in Figure 1, which contains of information supplied by the engine producers. From here, one can see that some transitions may occur slowly over time but some very rapidly (e.g. turbine blade damage), and thus the EMC's ability to quickly detect a change in trend is key. To meet this requirement, the engine parameters need to be acquired and analysed within steady-state intervals. Engine producers usually recommend performing manual engine health monitoring under comparable conditions during the cruise phase of the flight. This implies that the crew needs to identify the conditions and maintain the air speed, pressure altitude and all on-board system configurations at very similar and comparable levels. Recognition of such conditions and the ability to keep the flight steady during these measurement periods is then significantly influenced by crew capabilities and heavily affects the accuracy of measurements taken (Doel, 1994). Such inaccuracies add additional "noise", which impairs the detection of unexpected engine degradation. However, such a manual method is the best approach for achieving comparable conditions for engine health trend monitoring data collection. This procedure is best achievable in airliners with their typical standard flight profiles, but, nonetheless, not much of use for fluctuating flight profiles of the smaller GA airplanes.

In the case of smaller private turboprop airplanes, the situation is complicated mainly because of the wide variety in flight missions, ranging from cargo or passengers transport, surveillance, patrol, photographic or even airdrop flights. Because of this diversity of flight profiles, the process of engine power degradation monitoring becomes considerably complex. Achieving comparable or even equal flight conditions is not possible or is not economical for the prevailing number of flights. To demonstrate this variety, Figure 2 shows a recorded spectrum of private turboprop operation modes over a period of ten years and illustrates the wide range of basic flight parameters in which steady conditions were observed. From these three charts, one can clearly distinguish the individual flight levels at higher altitudes and from the right chart, the fact that the majority of the steady-state traffic intervals take place at altitudes of 7,600, 7,900 and 8,200 m ISA. Based on this flight mode distribution, in the further analyses, we use data from the steady-state intervals on these particular levels only. Furthermore, comparisons are performed only among data at the same flight levels as only these represent suchlike and analogous conditions.

Proposed method description

The initial step of the proposed approach begins with collecting steady-state situations (points) into clusters that would encompass the most suitable ambient conditions. This clustering process yielded several data sets with comparable flight conditions. For each set, an initial model encompassing the engine state at the beginning of its lifetime (at least as seen from the available data perspective) is assembled, and deviation trends in observed engine state parameters are analysed. Consequently, it is possible to track the trend deviations, detect an unexpected shift in each parameter and assume the possible degradation of some of the engine components. If such a detectable event occurs, it should appear in a similar way in most of the other clusters. Most, as many of the more distant clusters represent completely different flight conditions, a malfunction or slight damage may not manifest itself. On the other hand, in cases other than engine-related problems, such as a leak in the pressurised cabin due to a worn seal or a defective valve, an event of this kind could emerge only in a minority of separate clusters. In this particular malfunction scenario, the deterioration is expected to be more pronounced in clusters covering data from higher flight levels. The solution below may also offer another diagnostic input that could support locating the problem more accurately. Furthermore, one of the substantial issues is that the proposed method is required to reach at least the same precision as that defined by the engine producer, or even better, to exceed it.

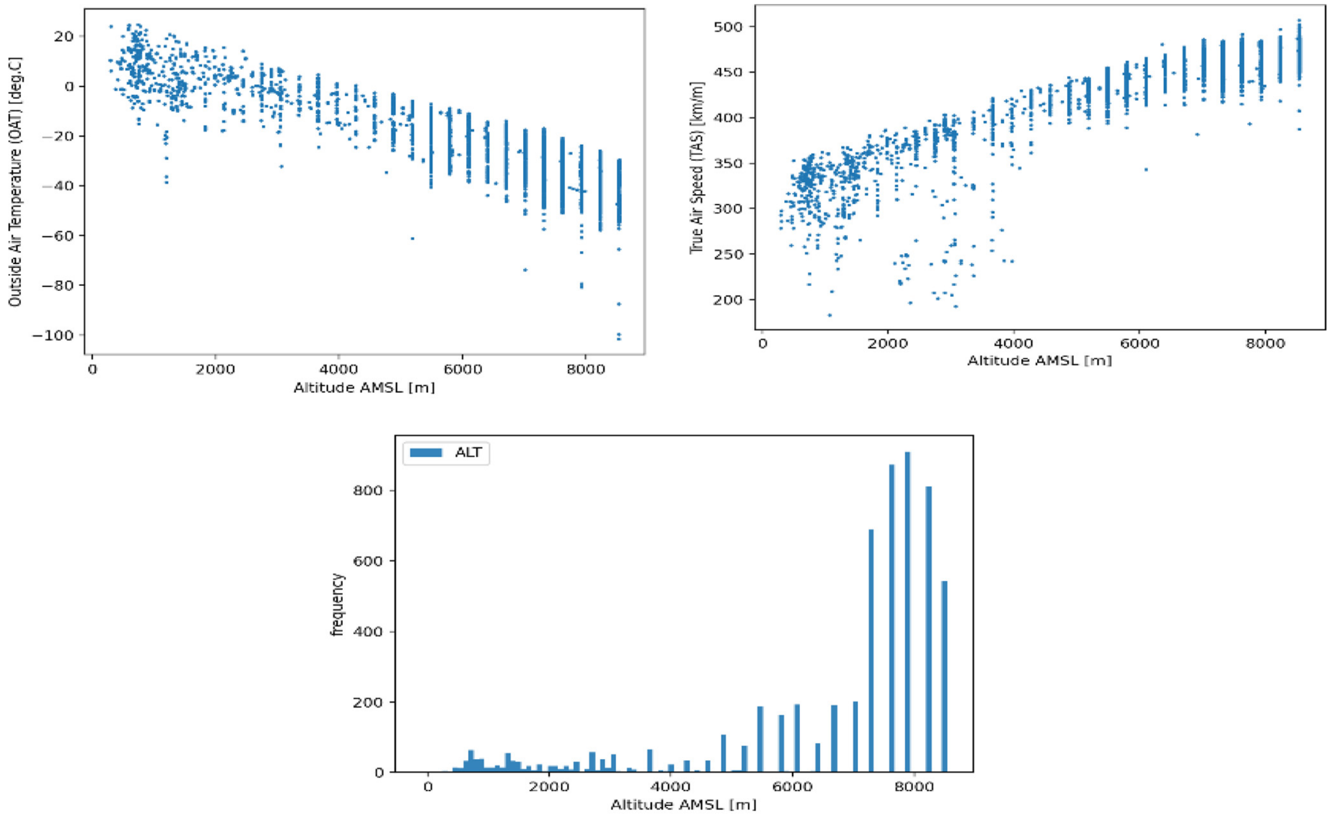
Figure 1 Typical patterns of parameter trending for various modes of damage. Summarised from the information gathered from the engine operating manual



Engine	Compressor				Compressor turbine	
Damage / Parameter	Compressor deposit / degradation	Air inlet restriction	Blade / Vane damage	Air leaks (bleeds, discharge valve)	Leaks	Blade / Vane damage
ITT	↑ ╱	↑ ⎽⎺	↑ ⎽⎺	↑ ╱ or ⎽⎺	↑ ╱ or ⎽⎺	↑↑ ⎽⎺
FC	↑ ╱	↑ ⎽⎺	↑ ⎽⎺	↑ ╱ or ⎽⎺	↑ ╱ or ⎽⎺	↑↑ ⎽⎺
NG	↑ ╱	↑ ⎽⎺	↑ ⎽⎺	↑ ╱ or ⎽⎺	↓ ╱ or ⎽⎺	↓ ⎽⎺
TRQ	↓ ╲	↓ ⎺⎽	↓ ⎺⎽	↓ ╲ or ⎺⎽	↓ ╲ or ⎺⎽	↓ ⎺⎽
Vibration	–	–	↑ ⎽⎺	–	–	↑ ⎽⎺

Notes: ↑,–trend direction; ⎽⎺ trend step change (rapid transition); ╱ trend slope change (protracted transition)
Source: Figure by authors

Figure 2 Overview of the basic flight parameter distribution in which steady conditions were recorded



Notes: Each point in the top two charts represents a satisfactory entry into a feasible ECM process, in which a certain necessary level of sensitivity to detect a sudden deterioration in engine performance needs to be achieved. The histogram at the bottom indicates the altitudes (at which flight levels) at which the most steady-state data points suitable for processing were available
Source: Figure by authors

The PT6A engine producer, Pratt & Whitney Canada, defines in the PT6A ECM section of the engine manual the following requirements and guidelines for trend interpretation:

- Net change of 10 to 15°C ITT: an early sign of deterioration that should be investigated when convenient.
- Net change of 20 to 25°C ITT: deterioration becoming more serious. Further running could result in replacement of some of the hot section components. Corrective action should be taken as soon as possible.
- Net change of 30°C ITT: at this level, whether or not ITT is redlined, deterioration has progressed to a point where serious engine damage is imminent.
- Net change of 0.75 to 1% NG: early signal of some deterioration should be investigated when convenient.
- Net change over 1.5% NG: action should be taken as soon as possible.

Hot section problems are all characterised by high ITT and FC (see Table 1). Gas generator speed values trend usually tends to go down or remain constant. The required sensitivity must be reached also during automated processing.

Monitoring the ITT deviation to detect oncoming deterioration in the selected clusters will be described in further detail. This parameter was selected because it most significantly indicates the potential engine problems. The ITT is closely related to the thermodynamic efficiency of the engine and its ability to provide the required performance. The thermal mode of the turbine also affects the service life of the hot section components of the engine. The significant dependence of the ITT value on the ambient air conditions is also known. Therefore, discrete flight levels of 7,600, 7,900 and 8,200 m according to the international standard atmosphere ISA (with a tolerance of ± 30 m) were chosen for the purposes of this study, as most steady-state data segments for air traffic of this particular aircraft are present at these altitudes, as shown in Figure 2 at the bottom.

Table 1 Correlation coefficient between ΔITT and ΔOAT for various compensation methods

Altitude/correlation	$\Delta ITT_{Std\ corr}$	$\Delta ITT_{OAT\ corr}$	$\Delta ITT_{NG\ corr}$
7,600 m	0.6912	0.5212	0.4324
7,900 m	0.727	0.5505	0.5505
8,200 m	0.7656	0.6806	0.599

Source: Table by authors

Data set description

This study was based on data obtained from a single-engine aircraft equipped with a PT64-42 engine. The data set was recorded using the Garmin G1000 system on an SD card covering 116 months of operation from 2013 to 2020, covering 1,386 individual flights. During this period, several engine service events that could affect the engine parameters were registered. Examples of such events include regular compressor wash procedures or the replacement of fuel nozzles. No shift in the trend parameters was observed in these cases. These events had no observable effect on the engine parameters.

The authors developed an algorithm for the detection of steady flight conditions in each flight (in which there can be multiple flights) and their subsequent assignment to clusters constrained by uniform altitude and engine torque. A steady state is defined as a data interval (window) with a maximal permitted deviation along such a window on multiple observed channels (like NG, ITT and others). The data-processing pipeline is defined as follows:

1 Data ingress and parsing of recorded files come from various sources and formats of most airplanes. Usually in for of an .csv text file on an SD card.
2 Detection of steady states. The data sections used for engine health monitoring need to be recorded during horizontal flights under the following conditions:
    - constant altitude, +/- 100 ft;
    - constant power settings torque +/- 100 ft/lb; and
    - time duration to avoid possible interference from transient events, such as engine cooling after a steep climb to the designated flight level. Furthermore, the duration of steady-state intervals needs to be of a certain minimum length. Depending on the nature of the airplane operations, it can vary from 60 up to 300+ seconds.
3 Data filtering and standardisation: Limit the influence of the ambient atmosphere conditions.
4 Calculation of delta parameters and creation of time graphs of delta parameters.

The monitored aircraft used a single-lever control system in which the propeller maintained a constant speed. This system reduces the number of parameters required for the steady-state detection. The only significant parameter that cannot be affected, which significantly affects the engine parameters, is the ambient air temperature (OAT). Hence, it is necessary to eliminate the influence of OAT.

Inter-turbine temperature standardisation description

As mentioned above, the measured ITT temperature must be compensated for to remove the influence of the OAT. Ideally, this compensated temperature would reflect the current state of the engine. However, as described below, this task is not straightforward. Three approaches are explored in this study. The results of the presented methods are presented in the form of deviations of the compensated ITT for better illustration. The ΔITT value was determined as the difference between the $\mathrm{ITT}_{\mathrm{Std\ corr}}$ value and the baseline according to equation (1). The average of the first five steady states was used to determine the baseline $\mathrm{ITT}_{\mathrm{base\ point}}$. The number of steady states was selected based on the limited number of available flights.

First compensating method

The first method is based on a commonly used method and is theoretically described by Daroogheh (2012). The principle is the conversion to ISA values using the dependence between ITT and OAT according to the following expression:

$$\mathrm{ITT}_{\mathrm{Std\,corr}} = \left((\mathrm{ITT} + 273,15)/\left((\mathrm{T}_{\mathrm{ISA\,0m}} + 273,15)/(\mathrm{T}_{\mathrm{OAT}} + 273,15)\right)\right.$$
$$\left. -273,15\,[^{\circ}\mathrm{C}] \right. \tag{2}$$

where:

$\mathrm{ITT}_{\mathrm{Std\ corr}}$ = corrected value of ITT (°C);
ITT = measured value of ITT (°C);
T_0 = measured value of ambient temperature (°C); and
$\mathrm{T}_{\mathrm{ISA\ 0m}}$ = reference value of ambient temperature for ISA 0 m altitude (°C).

The results of this compensation are shown in Figures 3, 4 and 5 in the form of $\Delta\mathrm{ITT}_{\mathrm{STD\ corr}}$. To present the results, a moving average of three values was chosen for data exclusivity protection; however, the character of the series was preserved. The dependence between $\Delta\mathrm{ITT}_{\mathrm{STD\ corr}}$ and deviation from the standard temperature at a given flight level can be observed, which is represented by the series marked as ΔOAT in the charts. This dependence was verified by correlation analysis for the given flight levels. Table 2 shows the correlation coefficients between OAT and ITT for the tested methods. Correlation coefficients ranging from 0.6961 to 0.7655 indicated a significant relationship. The results were validated using standard statistical indicators: average deviation mean deviation, max min, variance, trend line equation slope. The values are presented in Table 3. The authors tend to believe that this may be related to the position of the OAT sensor, which is on the fuselage, whereas the conditions in the engine inlet channel may be different.

Second compensating method

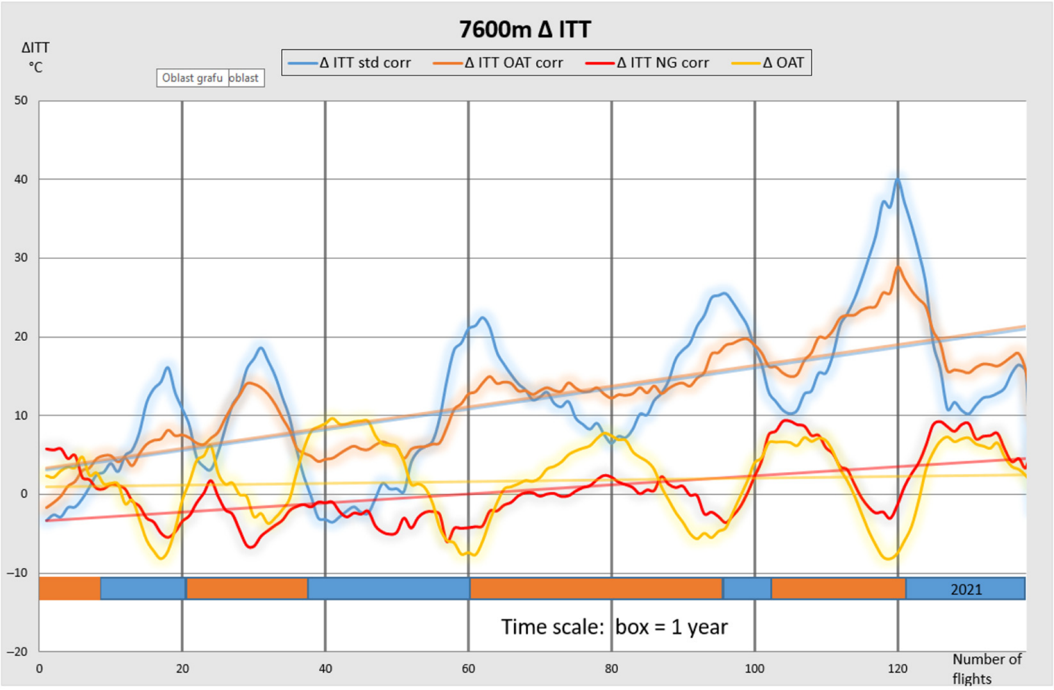
Because the correlation coefficients for the flight levels varied, a second method is proposed. It was verified whether the results would improve if the standard temperature for the flight level, which is defined by the ISA, was chosen as a common basis. This corresponds to temperatures of –34.1°C at an altitude of 7,600 m, –36.0°C at 7,900 m and lastly, –38.0°C at an altitude of 8,200 m. A linear method, according to equation (3) was used to compensate for the ITT. The compensation coefficient is derived from the operating characteristics of the engine declared by the producer in the PT6A-60 SERIES TRAINING MANUAL. The value of the coefficient was 3.4:

$$\mathrm{ITT}_{\mathrm{OAT\,corr}} = \mathrm{ITT} + (\mathrm{T}_{\mathrm{OAT}} - \mathrm{T}_{\mathrm{ref}})\mathrm{C}\ [^{\circ}\mathrm{C}] \tag{3}$$

where:

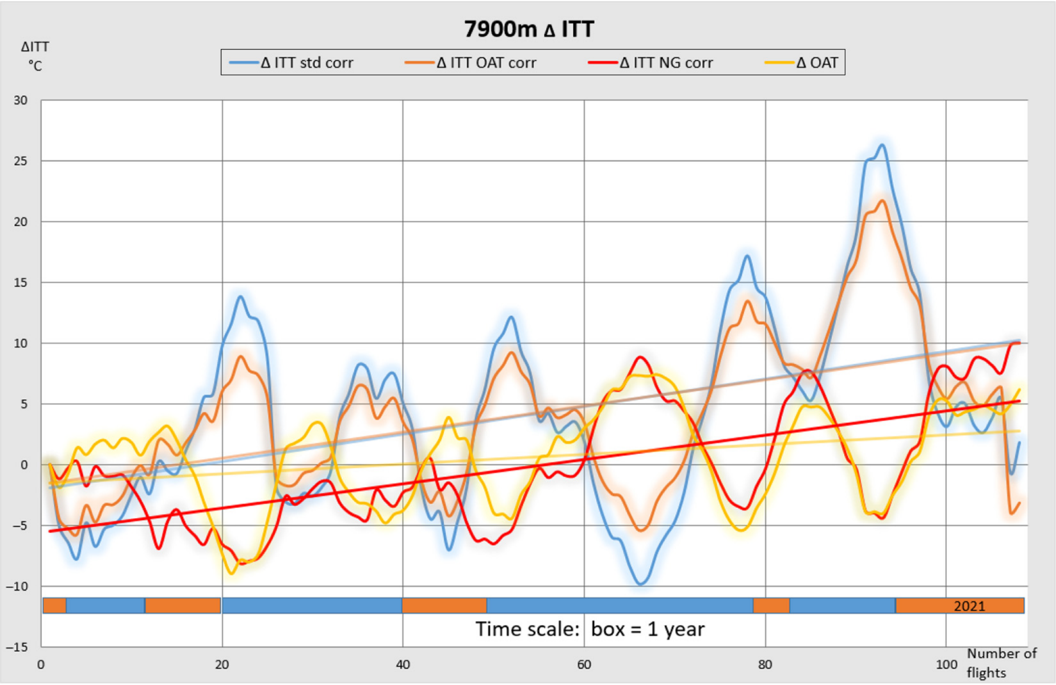
$\mathrm{ITT}_{\mathrm{OAT\ corr}}$ = corrected value of ITT; (°C);
ITT = measured value of ITT (°C);
$\mathrm{T}_{\mathrm{OAT}}$ = measured value of ambient temperature (°C);
$\mathrm{T}_{\mathrm{ref}}$ = reference value of ambient temperature for appropriate altitude according ISA (°C); and
C = compensation coefficient 3.4.

Figure 3 Comparison of the resulting ΔITT for the tested ITT compensation methods at altitude of 7,600 m ISA



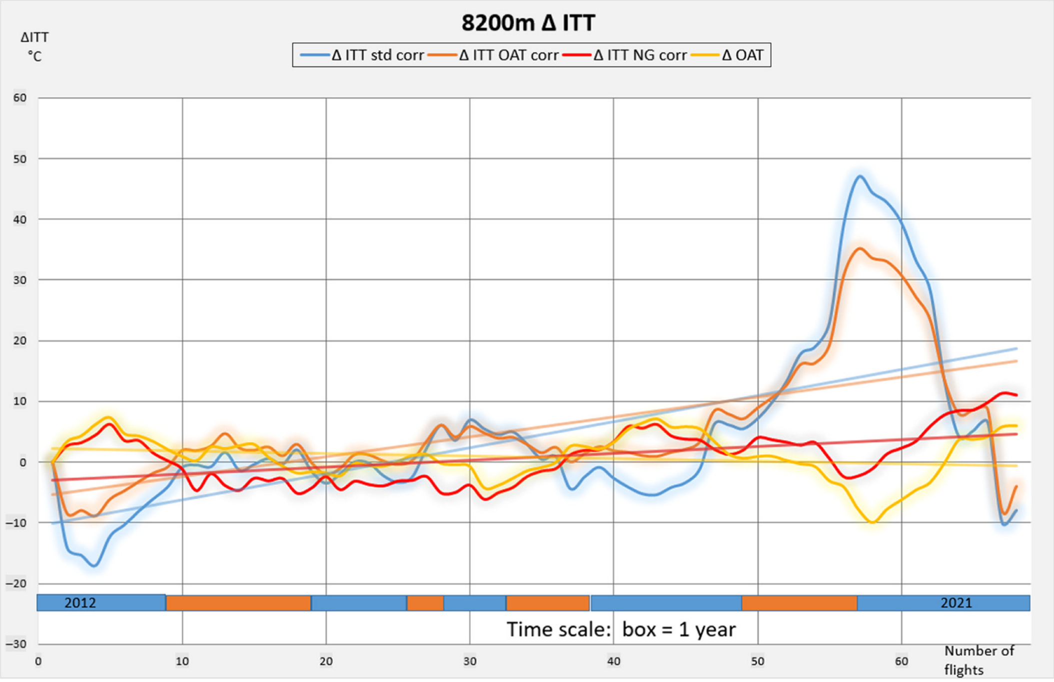
Notes: $\Delta\mathrm{ITT}_{\mathrm{Std\ corr}}$ (blue); $\Delta\mathrm{ITT}_{\mathrm{OAT\ corr}}$ (orange); $\Delta\mathrm{ITT}_{\mathrm{NG\ corr}}$ (red); ΔOAT (yellow)
Source: Figure by authors

Figure 4 Comparison of the resulting ΔITT for the tested ITT compensation methods at altitude of 7,900 m ISA



Notes: $\Delta\mathrm{ITT}_{\mathrm{Std\ corr}}$ (blue); $\Delta\mathrm{ITT}_{\mathrm{OAT\ corr}}$ (orange); $\Delta\mathrm{ITT}_{\mathrm{NG\ corr}}$ (red); ΔOAT (yellow)
Source: Figure by authors

Figure 5 Comparison of the resulting ΔITT for the tested ITT compensation methods at altitude of 8,200 m ISA



Notes: $\Delta ITT_{Std\ corr}$ (blue); $\Delta ITT_{OAT\ corr}$ (orange); $\Delta ITT_{NG\ corr}$ (red); ΔOAT (yellow)
Source: Figure by authors

Table 2 Statistical results for various ΔITT compensation methods

Altitude	Method	Average ΔITT (°C)	Median ΔITT (°C)	Max ΔITT (°C)	Min ΔITT (°C)	Scatter ΔITT (°C)	ΔITT SD (°C)
7,600 m	$\Delta ITT_{Std\ corr}$	4.64	18.72	52.95	0.71	132.7	8.39
	$\Delta ITT_{OAT\ corr}$	−11.81	9.14	44.2	5.72	70.41	11.52
	$\Delta ITT_{NG\ corr}$	2.89	−0.18	14.24	−6.36	35.17	5.23
7,900 m	$\Delta ITT_{Std\ corr}$	12.62	16.27	44.84	−17.91	87.22	9.34
	$\Delta ITT_{OAT\ corr}$	−1.77	−1.69	32.79	−13.03	162.58	12.75
	$\Delta ITT_{NG\ corr}$	1.72	0.85	16.73	15.47	52.5	7.24
8,200 m	$\Delta ITT_{Std\ corr}$	4.64	16.67	107.03	11.45	225.36	15.01
	$\Delta ITT_{OAT\ corr}$	−11.81	−7.75	75.43	−12.81	404.57	20.11
	$\Delta ITT_{NG\ corr}$	0.76	1.29	13.82	−14.33	52.12	7.2

Source: Table by authors

The results of the second method are shown in Figures 3, 4 and 5 as $\Delta ITT_{OAT\ corr}$ series. This method showed a lower correlation coefficient than the first method from 0.5212 to 0.6906; see Table 2. Further statistical evaluation according to Table 3 shows the substantial variance of this method. Both evaluated methods had a larger variance in the ΔITT. This variance can lead to a false indication of engine problems. This is higher than the engine producer recommendation stated above. Many false indications require manual data verification and increase the cost of the monitoring systems. To eliminate automatically generated warnings, the variance should not exceed 10°C.

Third compensating method

There is a problem with the placement of sensors in the Garmin system, which complicates the determination of the air temperature in front of the engine compressor. Therefore, the ITT compensation method using NG generator revolutions was evaluated. This method is based on the observed dependence between NG and OAT. The relationship between these values was determined using the engine principle. When the engine maintains a constant propeller speed during flight and produces a constant torque, the NG speed responds to the mass flow passing through the engine. This can change as a result of variations in the air density or engine degradation. The reference speed NG was determined to be the speed corresponding to the ISA temperature for a given altitude. Equation (4) was used to calculate the compensated temperature:

$$ITT_{NG\,corr} = ITT + (NG_{OAT} - NG_{ref})C_{NG} \; [^{\circ}C] \qquad (4)$$

where:

$ITT_{NG\,corr}$ = corrected value of ITT; (°C);
ITT = measured value of ITT (°C);
NG_{OAT} = measured value of NG for a given ambient temperature (°C);
NG_{ref} = reference value of NG for ambient temperature at an appropriate altitude according ISA (°C); and
C_{NG} = compensation coefficient 8.9.

The results of this approach are shown in Figures 3, 4 and 5 as $\Delta ITT_{NG\,corr}$. The detailed statistical results are presented in Tables 2 and 3. This method has shown good results and low sensitivity to changes in OAT and the variance of the method is low. This compensation could be suitable for automated evaluation of possible abnormalities.

Discussion of findings and results

From the charts in Figures 3, 4 and 5, it can be observed that the traffic intensity at the observed levels varies. This is because of the customer requirements for the flight routes. During the monitoring period from 2012 to 2021, 140 flights at an altitude of 7,800 m, 102 flights at an altitude of 7,900 m and 68 flights at an altitude of 8,200 m were recorded. This complicates the monitoring of trends in key engine parameters. Therefore, it is necessary to determine the deviations of the monitored parameters with minimal external influences. During the testing, a certain dependence of the ITT on the ambient temperature was observed using the usual compensation methods. The observed dependence may result from the method of temperature measurement by an avionic system where the OAT temperature is measured by a probe on the aircraft. Hence, the temperature was not measured before the compressor. Therefore, an ITT correction method based on NG compensation was tested. Because the nature of the operation of the monitored aircraft does not allow for continuous monitoring at one level, the detected ΔITTs through NG compensation a plotted in Figures 3, 4 and 5. A change in the ΔITT of more than 10°C according to the engine producer indicates a possible problem. It can be seen from the graphs that the average $\Delta ITT_{NG\,corr}$ value varies in the interval ± 10°C. The +10°C interval was exceeded at 11 points during the monitored operation. A detailed graph cannot be provided because of project partner data protection requirements. The analysis of these outlier points revealed small deviations in the torque parameters. The frequency of occurrence is 1–2 times per year, which is acceptable for automatic monitoring. The method was tested only on a healthy engine. Table 1 indicates that a series of engine failures will manifest as change in both the ITT and NG. It is assumed that in the event of a potential fault, these effects could increase the deviation from the baseline value. The authors plan to verify this hypothesis in the future by simulating engine failure by increasing the air bleed flow from the compressor for longer periods of time.

Conclusion

The authors are not aware of a study that would comprehensively deal with the influence of real flight conditions on engine parameters; therefore, they consider the present study beneficial. This paper demonstrates on a real example an ECM implementation approach based only on the data recorded by common on-board avionics without the use of any special equipment or sensors. If the required engine wear monitoring sensitivity can be achieved with conventional instrumentation, such an ECM could be of great interest to many private owners and operators, because of the potential savings on additional on-board equipment. For example, many specialised ECMs use pressure sensing behind the compressor, which improves sensitivity and accuracy but also imposes additional costs on users and, most importantly, may not be available for certified or smaller engines. The study presented in the article suggests that despite all the compensation efforts, there are still significant fluctuations in ΔITT depending on the flight parameters. Even small changes in the flight parameters can cause significant ΔITT fluctuations. In future research, the authors plan to focus on the accurate quantification of these effects.

The problem of the effect of OAT on the inter turbine temperature can be compensated for by the NG generator speed, as the generator speed is controlled by the engine system based on its sensor data. This method may not be accurate for detecting specific engine faults but can serve as a warning trigger in an automated system. The aim of this development is to propose an ECM based on readily available data to provide a maximally automated and accurate open ECM. The study presented in this paper suggests that despite all compensation efforts, there still is a significant dependence of ITT on flight parameters that need to be dealt with.

A large number of altitude- (or other parameter)-based clusters with a narrow range of defined environmental conditions, such as ISA, TRQ or altitude, have the potential to increase sensitivity of this method. However, the wide variety in flight missions of smaller airplanes limits the number of useable data points in clusters that can be used for this type of analysis. Should this research continue, the authors aim to focus on the multiparametric compensation of ΔITT trends to increase accuracy and eliminate false alarms.

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