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TREND MONITOTING OF TURBOPROP ENGINES

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Abstract

The paper describes an approach to the diagnostics and evaluation of trend behavior of aircraft turboprop engines. The diagnostics of data from engine verification tests during its lifespan between production and overhaul is described and suitable parameters for the evaluated thermodynamic engine state are identified and discussed. The authors chose a method of single-parameter regression analysis using a second-degree polynomial function and applied the proposed procedure to flight measurements. Furthermore, the findings discovered during a long-term monitoring process of an available turboprop engine are presented.

Keywords: turboprop, trend monitoring, health monitoring

1. Introduction

Aircraft gas turbine engines have a unique place in aviation due to their characteristic features. They allow to produce high performance at low weight and with minimal vibration. Also, their service life and reliability of gas turbines is much higher compared to piston engines. On the other hand, the selling price and maintenance costs of these engines are significantly higher. It is therefore logical that operators try to take advantage of the maximum economic efficiency of engine operation. Engine manufacturers strive to offer engines with prolonged service intervals, low number of time-limited parts and increased operation life. However, such objectives need to be balanced with the requirements for the safe operation of these engines appointed by aviation certification authorities.

The progress of electronics and digitalization make it possible to meet both goals at the same time. Complex mechanical regulation and control systems of turbines are substituted by advanced digital-based systems that enable precise control and continuous verification of the engine's measurable operating parameters. These systems, known as FCU (Fuel Control Units) or FADEC (Full Authority Digital Engine Control) [5], dominate civil aviation and thanks to their expansion find their way to smaller power-units such as turboprop engines. However, the increased acquisition costs which involve development and certification of these systems need to be balanced by the benefits to final customers – owners and operators. FCU control systems notably simplify engine control which, as a result, can be implemented as a single lever without any other control elements. In addition to this improved fuel efficiency and especially extended service intervals are a significant benefit. All operators strive to utilize their engines as efficiently as possible and with the most optimal load settings as the cost of overhaul is a significant item on their list of expenses.

Extension of service intervals must be performed in a way to minimize negative impact on engine operation safety and without increasing the risk of engine failure due to damage or excessive wear. One of such means are engine condition monitoring systems (ECMS) which must be sufficiently reliable and robust. These systems for gas turbines have been in development for over 70 years. Their development began practically with the arrival of the very first turbines. However, the area of application is still expanding into the environment, which, however, complicates their full use.

One such example are modern turboprop engines operated in general aviation airplanes. These engines are operated in smaller numbers under various operating conditions with a vast variability in flight profiles. And many such issues represent a great challenge to engineer a reliable ECMS.

At present, global manufacturers have introduced various systems for recording operating parameters not only before installation on the aircraft and after its suspension, but also continuous data recording.

An example is the Canadian engine manufacturer Pratt & Whitney which offers to the operator a continuous monitoring of the aircraft and its parameters through integration of the GARMIN avionics system.

This article therefore aims to assess algorithms applicable to the evaluation of parameters and quality deterioration or consumption of engine life and attempts to suggest feasible procedures for the evaluation process. The problem is the accessibility of this data, the way they are processed and the evaluation of outputs with an appropriate impact to the engine operator. Therefore, also for the needs of a more accurate and own, i.e., open, evaluation system, the following analyses and evaluations were performed

2. State of Art

A general view of a turboprop engine can be seen as a machine that converts chemical energy into mechanical work. From this point of view, the engine monitoring can be divided into two parts. Monitoring of the thermodynamic engine process in an effort to evaluate its efficiency and effectiveness, and monitoring the mechanical condition of the engine.

The monitoring of the mechanical condition of the set is usually described by mechanical quantities, such as vibrations or engine power. These are then part of separate analyses, with regard to anomalies of high-frequency and low-frequency vibrations depending on excitation (generator turbine speed or propeller) and are not the subject of this article.

The paper is focused on the thermodynamic process, where the engine is perceived as a device into which a mass of air of a certain weight enters at a given speed, which after adding fuel and burning releases energy, which subsequently turns into mechanical work on the shaft (see Fig. 1).

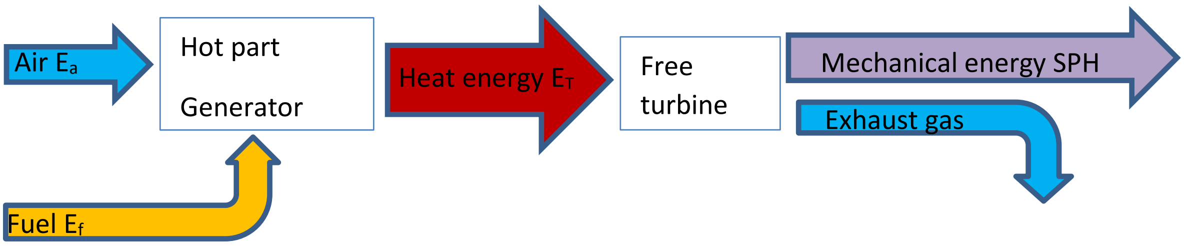

Figure 1 – Energy diagram of turboprop engine.

From this point of view, the parameters describing the individual energies can then be identified. For the following procedure, the energy per unit time, i.e. [J / s] = [Kgm2s-3] is used. It is done by using of mass flow $m^{/}$ (kg/s), which enters the cross section of a given area A (m2) at a given air speed in the input channel v_1 (m/s) into the engine. To describe the specific energy, depending on the available parameters at engine inlet, is used:

$$E_a = f(p_1, T_1, NG) \tag{1}$$

Fuel then enters into this system with its calorific value, i.e., we can again express it as the energy entering the engine E_f given by the fuel flow FC in kg/s. Subsequently, we can evaluate the energy output from the hot gas generator, which we can describe again. Here we are interested in the parameters of pressure behind turbine p_4, temperature behind gas turbine (T_4 or ITT), and flow rate given by turbine speed NG. Of which then:

$$E_T = f(p_4, T_4, NG) \tag{2}$$

The next part of the engine i.e., the free turbine and the gearbox, then converts the incoming specific energy E_T into the mechanical power on shaft SPH, given by the torque TQ and the propeller speed NP and the energy of the exhaust gasses:

$$SPH = f(TQ, NP) \tag{3}$$

From the above, we can compile an overview of parameters (see below) which are significant for description of the engine ‘s operation at an acceptable level. Methods of identifying a possible fault condition or changes in engine parameters and subsequent trend analysis are different. The authors used methods based on regression analysis. In trend analysis, the current problem is data standardization as the required deviation is usually lower than the accuracy of the method. Statistical methods or fuzzy methods are also often proposed. Very modern is the approach using artificial intelligence which may become very complex on a professional level.

2.1. Standardization of input data for analysis

For further analyses, it is necessary to select appropriate data sections and also to define comparable operation conditions.

The following parameters for evaluation of engine thermodynamic work have been used:

• surrounding atmospheric pressure	p_0 [Pa]
• surrounding atmospheric temperature	T_0 [^{0} C]
• flight speed (true air speed)	TAS [ms^{-1}]
• fuel consumption	FC [kgs^{-1}]
• gas pressure behind compressor	p_2 [Pa]
• gas temperature behind compressor	T_2 [^{0} C]
• gas pressure between turbines	p_4 [Pa]
• interstage turbine temperature	ITT [^{0} C], T_4 [^{0} C]
• gas turbine speed	NG [RPM, min^{-1}, %]
• propeller speed	NP [RPM, min^{-1}]
• torque moment	TQ [Nm, %]
• power on shaft	SPH [kW]

After data collection, let's approach its “standardization”. It is recommended to evaluate change of these parameters comparing to the standard atmospheric conditions, to eliminate the influence of the surrounding atmosphere changes or directly the parameter change at the engine inlet. Based on general experience [4], these parameters are recalculated as follows:

- Interstage Turbine Temperature - ITTR [°C]:

$$ITT_R = (ITT + 273{,}15)\left(\frac{T_{ISA_{0m}}+273{,}15}{T_0+273{,}15}\right) - 273{,}15 \tag{4}$$

- Gas turbine speed - NG_R [%]:

$$NG_R = NG\sqrt{\frac{T_{ISA_{0m}}+273{,}15}{T_0+273{,}15}} \tag{5}$$

- Propeller speed - N_{PR} [min^{-1}]:

$$NP_R = NP\sqrt{\frac{T_{ISA_{0m}}+273{,}15}{T_0+273{,}15}} \tag{6}$$

- Torque - TQ_R [Nm]

$$TQ_R = TQ\left(\frac{p_{ISA_{0m}}}{p_0}\right) \tag{7}$$

- Engine power on shaft - SPH_R [kW]:

$$SPH_R = \frac{TQ}{1000}\,\frac{2\pi NP}{60}\left(\frac{p_{ISA_{0m}}}{p_0}\right)\sqrt{\left(\frac{T_{ISA_{0m}}+273{,}15}{T_0+273{,}15}\right)} \tag{8}$$

- Fuel consumption - FC_R [kg.s^{-1}]:

$$FC_R = Q_F\rho_F\left(\frac{p_{ISA_{0m}}}{p_0}\right)\sqrt{\left(\frac{t_{ISA_{0m}}+273{,}15}{t_0+273{,}15}\right)} \tag{9}$$

, where Q_F and ρ_F are fuel flow and fuel density.

2.2. Engine failure identification

Based on expert experience [3] the following indicators can be used to evaluate the condition of the engine:

a) basic indirect status indicators
   - ITT - carries information on the conversion of chemical energy into thermal energy and at the same time limits the engine. Because the measurement point is located behind the generator turbine it can also be used to detect a problem on the generator turbine itself (the damaged turbine is not able to process the thermal energy in the exhaust gas which leads to an increase in ITT).
   - FC - Carries information on engine efficiency. A worn or damaged engine has lower efficiency; therefore, the engine needs more input power to produce the same amount of output power. NG - is tied to the mass flow that passes through the engine and it can be used to identify the problem on the compressor side.

b) other indicators
   - NP - to some extent it can be used to detect a problem on the selected turbine, a problem of influencing speed by the propeller regulator, for example, changing the frequency of the speed oscillation around the set value. With accurate measurements it may be possible to diagnose the condition of the propeller controller.
   - P2 – (compressor pressure) together with the total compressor inlet pressure can be used to determine the total compression. This can be used to establish compressor efficiency and to compare to known efficiency maps to determine deviations. This method is currently not very accurate due to the need to simplify the calculations of flow vibration neglect and requires accurate operating characteristics for the compressor. Unfortunately, these are usually available solely to the engine manufacturer. Currently, the greatest benefit of this method can be seen in stationary energy turbine analyses where accurate air flow measurements are possible.

Overview of engine troubles are shown in Table 1 below:

Table - 1 Component fault cases (CFC) indication

	Compressor				Combustion chamber	Generator turbine	
Failure	Deposits on the shoulder blades compressor	Entry restrictions	Damage to the blades	Leakage eg drain valve	Damage Typically damage to the pennant	Leak	Damaged blades / rotors
ITT	↑	↑	↑	↑	↑	↑	↑↑
FC	↑	↑	↑	↑	?	↑	↑↑
NG	↑	↑	↑	↑	?	↓	↓
TQ	↓	↓	↓	↓	?	↓	↓
P3	↓	↓	↓	↓	?		
Vibration	-	-	↑	-	-	-	↑

3. Function relations definition – ground tests

To describe the run of the engine both ground and flight measured data were used, in order to find independent parameters and their interrelationships to observe shift in engine behaviour.

Firstly, data from ground brake tests were analysed. The analysed data sourced not only from new engines immediately after production but also from units before overhaul. A total number of eight engines was used. The first evaluation step of the parameters obtained from the measurement was the evaluation of the engine while running at the manufacturer's test room. The relationships between the above-described parameters are shown in Tab 1.

Evaluation of the direct or indirect dependence of individual parameters (see Table 2) shown the following correlation coefficient (for $R^2 > 0.9$):

- generator speed is linked to propeller speed, temperature behind compressor, ITT and outlet nozzle temperature,
- propeller speed (output shaft) correlates with fuel consumption, power, temperature behind the compressor, ITT, pressure in the torque meter and pressure behind the compressor.

- torque correlates with propeller speed, fuel consumption, power, temperature and pressure behind the compressor, and pressure in the torque meter,
- fuel consumption correlates with propeller speed, torque, power, temperature and pressure behind the compressor, and pressure in the torque meter,
- shaft power correlates with propeller speed, torque, fuel consumption, inlet temperature, and pressure behind the compressor, and pressure in the torque meter, pressure behind the compressor, and pressure in the torque meter,
- the temperature behind the compressor correlates with generator and propeller speeds, torque and fuel consumption, ITT, outlet nozzle temperature, torque meter pressure, and pressure behind compressor,
- the temperature in the outlet nozzle correlates with the speed of the generator, and the temperature and compressor, ITT, oil and oil pressure.
- the pressure in the torque meter correlates with propeller speed, torque, fuel consumption, power, and compressor pressure (significantly),
- compressor pressure correlates with propeller speed, torque, fuel consumption, power, ITT and torque meter pressure,
- oil temperature correlates with generator and ITT speeds.

Based on above mentioned findings, generator speed, propeller speed, torque, fuel consumption, power, ITT, compressor temperature and pressure, and oil temperature were selected as the significant parameters for long-term engine behaviour monitoring. Also, temperature and pressure behind the engine compressor can be considered as very suitable thermodynamic independent parameters for engine monitoring.

Table 2: Correlation coefficients for measured parameters resulting from ground and flight tests

Parameter	Parameter	Correlation coefficient		
		Laboratory	Flight (R0)	Flight (R1)
NG	NP	0,950		
NG	ITT	0,965	0,9867	0,9867
SPH	TQ	0,991		
SPH	FC	0,973	0,9849	0,9851
SPH	ITT	0,766	0,9698	0,9702
SPH	P2	0,970	0,9906	0,9702
SPH	T2	0,878	0,9856	0,9864
SPH	NG	0,761	0,9885	0,9882
FC	NG	0,888	0,9969	0,9967
FC	ITT	0,877	0,9915	0,9917
FC	P2	0,994	0,9914	0,9916
FC	T2	0,956	0,9971	0,9971
FC	NP	0,970		
FC	TQ	0,989		
ITT	T2	0,939	0,9888	0,9881
ITT	T5	0,981		
TQ	T2	0,927		
TQ	P2	0,990		
NG	T2	0,961	0,9966	0,9981
NP	T2	0,982		
NP	P2	0,973		
T2	P2	0,965	0,9914	0,9944

In an effort to better describe the behaviour of the engine, an n-parametric function was created using regression analysis. For example, relations like TQ=f(p_0, T_0, NG, NP, FC, ITT, p_2) were created, alternatively also with smaller number of selected parameters (NG, NP, FC, ITT, p_2) or with other arguments, e.g. ITT=f(p_0, T_0, NG, NP, FC). Accuracy of the measured data fitting was evaluated in nominal modes for individual engines in the state of release from production and before overhaul. The subsequent evaluation of the accuracy of the obtained values for the nominal variable indicated a deviation from the nominal value in tens or hundreds of percent. This procedure proved to be significantly influenced by the accuracy of individual parameters and subsequently also regression coefficients, that it was not possible to accept it for the evaluation of fine deviations of engine characteristics.

Hence a simpler functional relationship was appointed in the form of individual dependence of only two parameters. Obtained correlation coefficients are then given in Table 2 (column "laboratory"). From those here parameters can devise the significant ones in terms of accuracy (assuming a steady state) are relations:

- $SPH_R = f(NG_R)$
- $ITT_R = f(NG_R)$
- $FC_R = f(NG_R)$
- $ITT_R = f(SPH_R)$ (10)
- $FC_R = f(SPH_R)$
- $FC_R = f(ITT_R)$

Furthermore, the following ones also seem to be of a valuable nature:

- $SPH_R = f(P2_R)$
- $SPH_R = f(T2_R)$
- $FC_R = f(P2_R)$
- $FC_R = f(T2_R)$ (11)
- $ITT_R = f(P2_R)$
- $ITT_R = f(T2_R)$

Unfortunately, second ones are not usable for evaluation due to absence of appropriate sensors in the standard equipped engines.

Furthermore, a comparison of the impact of some identified defects was made. An example is the impact of carbon deposition in the combustion chamber and damage to the leading edge of the blades, which is identifiable depending on the dependence of ITT_R on SPH_R (see Fig. 2), or the dependence of FC_R on SPH_R.

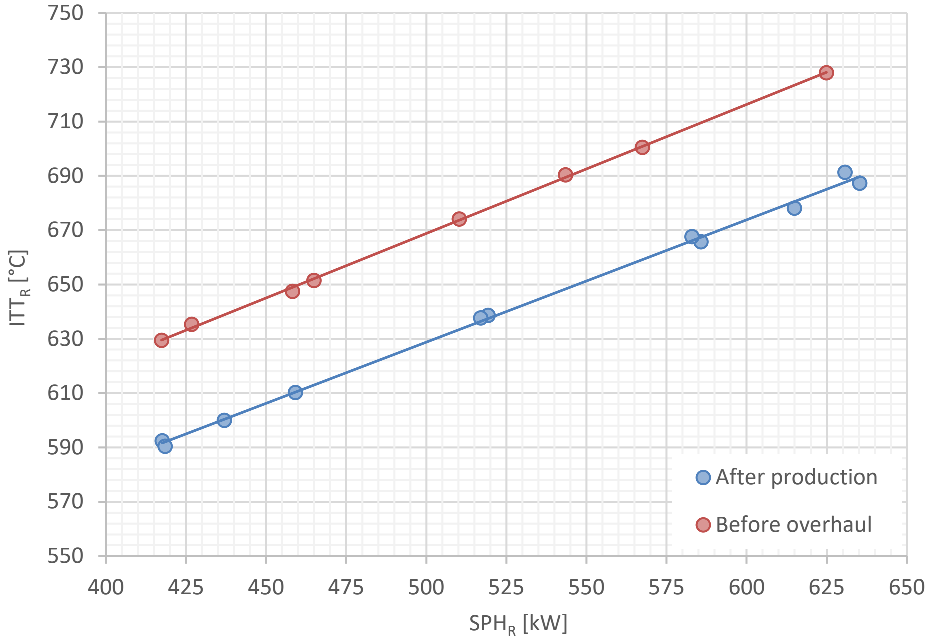

Figure 2 – Comparison engine parameters after production and before overhaul.

Similarly, it was possible to identify damage to the first compressor stage by the impact of a foreign object with the same parameters. The engine showed symptoms typical of damage to the compressor part, but the increase in fuel consumption was not significant. The reason could be the specified power, which is calculated from the torque and speed. Therefore, the dependence on consumption on TQ was evaluated. Here, the increase in fuel consumption is better identifiable.

4. Function relations definition – flight tests

The evaluation of parameters from flight recordings followed. A standard engine additionally equipped with a pressure and temperature sensors behind the compressor and the engine inlet was used for the experiment. Other sources of influence were added to the original parameters such as bleeds from the engine for the needs of heating or pressurization of the aircraft's cabin. The obtained characteristics for evaluation were recalculated to the standardized values with regard to the conditions of the surrounding atmosphere of the aircraft (as R0), but also the conditions at the engine input (R1). Two-parameter dependences were then created from the obtained data (see Fig. 3 and Fig. 4) with a very good correlation coefficient (see Table 2).

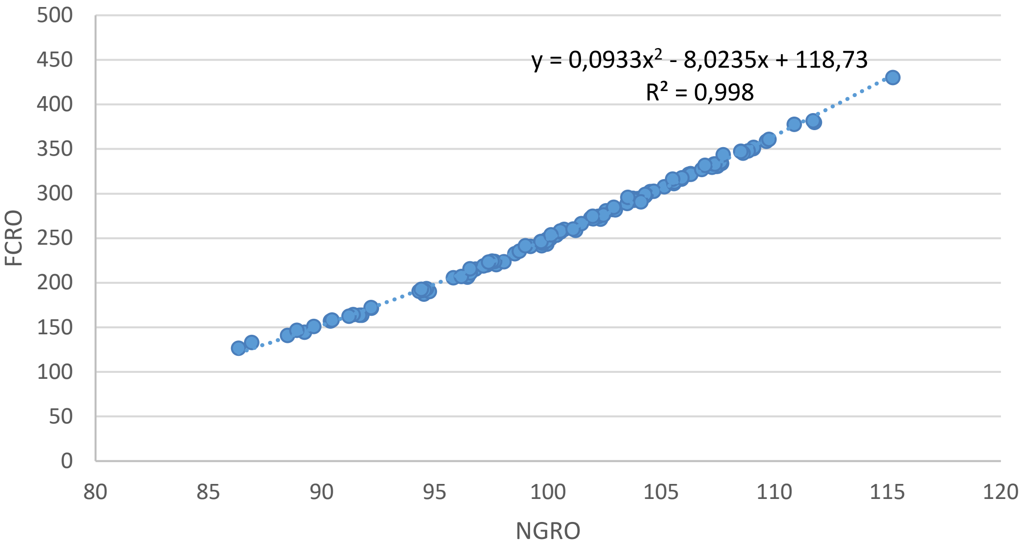

Figure 3 - Fuel flow on turban speed

By comparing the individual correlation coefficients, it is possible to state the acceptability of the conversion to the conditions of the surrounding atmosphere. Next, importance of measuring the parameters behind the compressor was confirmed. It`s very significant correlation dependence shows significant monitoring potential.

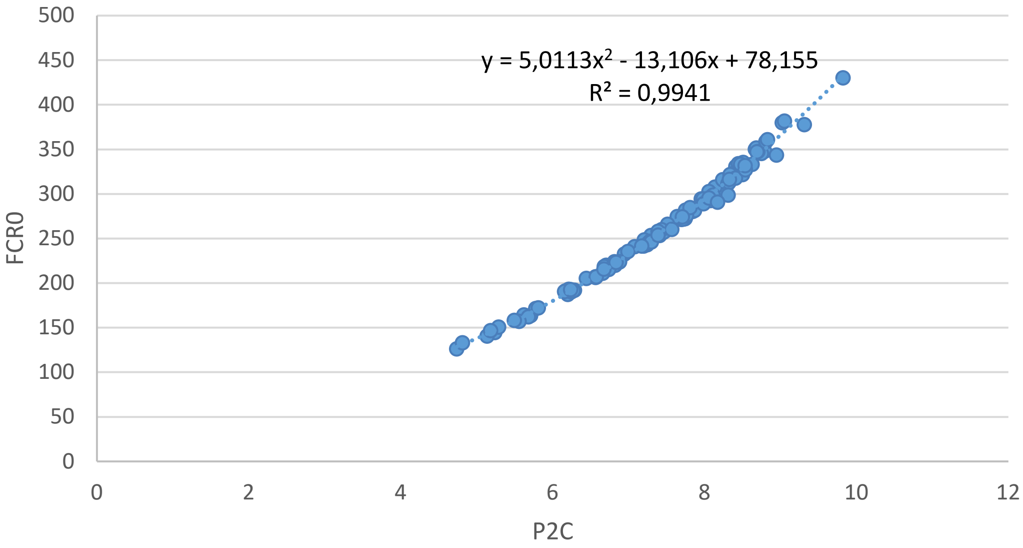

Figure - 4 Fuel flow as a function of pressure behind compressor

5. Application of method to real engine

Above results then give the opportunity to apply them to a real engine. The following procedure was set-up and applied on a PT6 engine. Trend monitoring analyses were performed on 1846:37 flight hours and 1574 cycles. However, the proposed approach encounters the absence of initial parameters, i.e., engine characteristics after production or overhaul.

Therefore, in the first step as part of the initial calibration a set of “standardized curves” was defined (see Fig. 5), which is unique for each individual engine. The standardized data of stable continuous operation mode was compiled from the initial 50 flight hours. This step defines the initial characteristics for a completely new engine or after overhaul. These were determined in an equal way to previous flight measurements, i.e., the data were standardized (see equations (4) - (10)), then quasi-static intervals with a duration of at least 4 minutes were selected and then regression analysis with a second-degree polynomial was performed for selected dependencies (10).

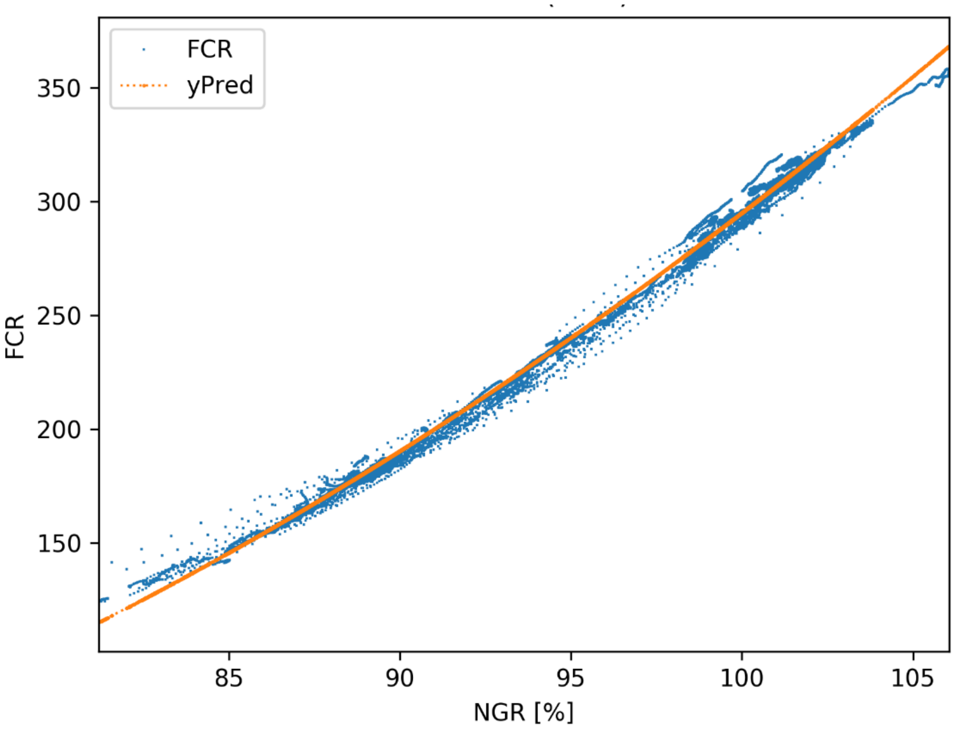

Figure 5 - Initial curve of Fuel flow as a function of gas-generator speed

The second step then followed by evaluating individual flights so that for each flight the functional dependencies were created from the quasi-static intervals. That established a set of standardized parameters on which polynomials were calculated. Next, the delta of the dependent parameters was determined between the standardized curves and the current individual flight curves for average value of independent parameters of a particular flight.

As an example, see Fig. 6 in which the parameter ITT_{R0} as a function of NG_{R0} is plotted. Each flight is denoted by a single point, expressing deviation value of the calculated ITT.

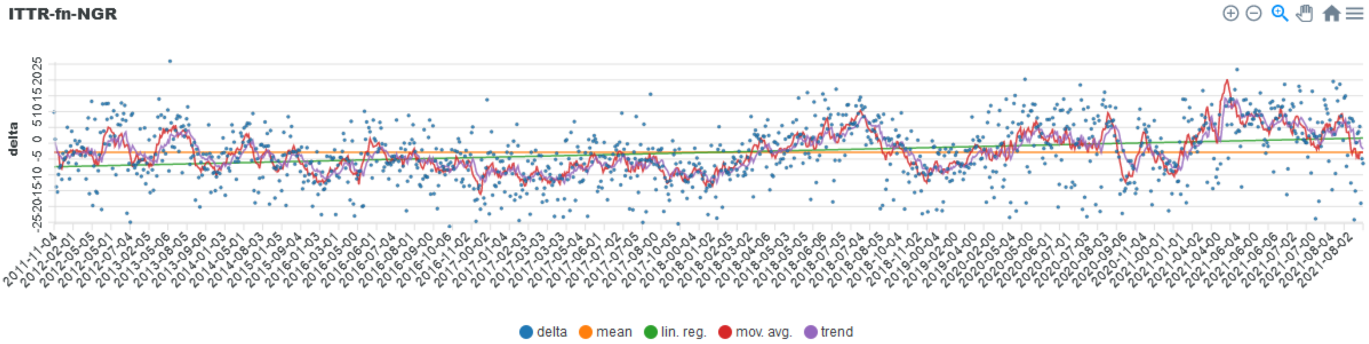

Figure - 6 Trend monitoring diagram ITT$_{R0}$ = f(NG $_{R0}$)

5.1. Evaluation of engine behaviour trend

Subsequently, it is then possible with regard to individual engine cycles to identify the tendency of engine behavioural characteristics over time. In this particular described case, the linear regression is outlined in Fig.6 as green line, which indicates a gradual increase in temperature within the turbine rising with the number of engine cycles.

Other characteristics with the identification of anomalies are processed in a similar way. Another example is the following Figure 7 of the turbine output power as a function of the generator turbine speed. The highlighted area shows the effect of service intervention.

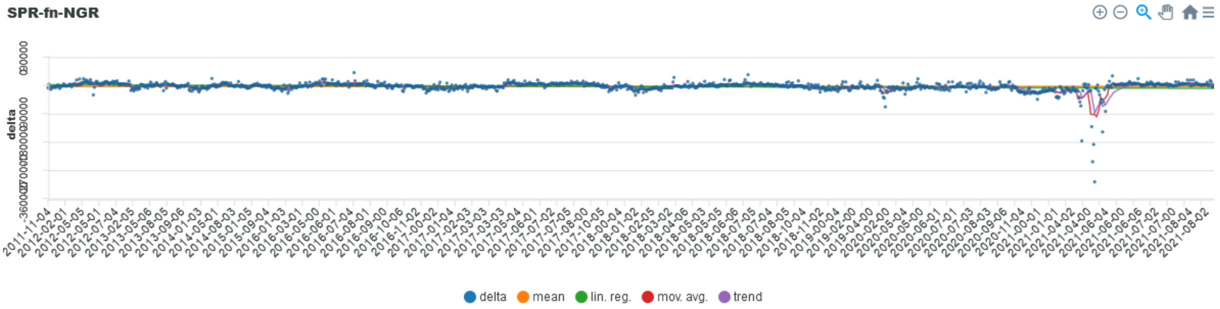

Figure - 7 Trend monitoring diagram SPH $_{R0}$ = f(NG $_{R0}$)

Similarly, the equal problem arises on the chart of fuel consumption as a function of the generator turbine temperature.

As can be seen from both presented charts in (Fig. 6, Fig. 8), there is a notable increase in deviations from the initial values of the ITT and FC characteristics. Due to the relatively small deviations, it can be declared that the trend was captured but so far it has not meant such a gradient of change that service intervention is necessary.

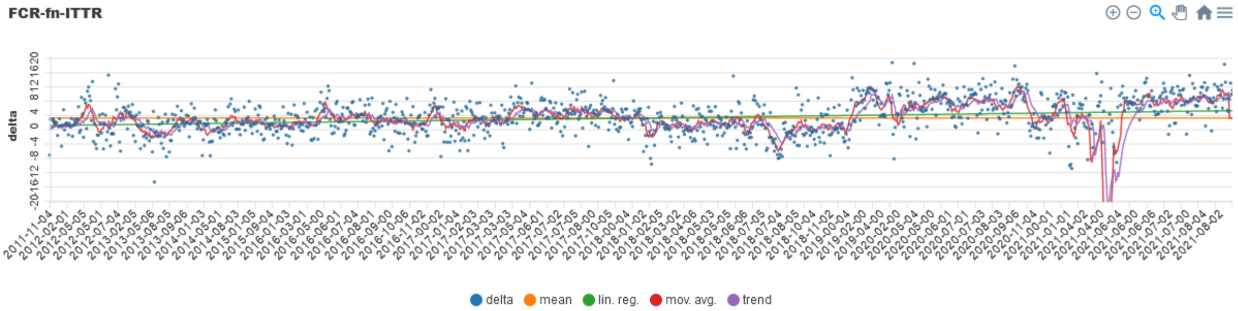

Figure - 8 Trend monitoring diagram FC $_{R0}$ = f(ITT $_{R0}$)

6. Conclusion

It is clear that engine monitoring is a significant contribution to the continuous assessment of engine behaviour and the early identification of possible behavioural anomalies.

A method of thermodynamic engine state identification was introduced based on individual single-parameter dependences of individual parameters and their mutual comparison after individual cycles. Reliability assessment of the method and identification of the cause continue in verification for which a wider variety in engines, range of flight missions and larger number of recorded flight hours are needed. For this a close cooperation with an engine manufacturer or a frequent operator would be of a tremendous benefit.

Furthermore, it turns out that a temperature and pressure sensors behind the engine compressor, which are not present on many engines, can be an important and highly useful source of monitoring parameters.

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Copyright Statement

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