CHEMICAL ENGINEERING TRANSACTIONS
VOL. 46, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Peiyu Ren, Yancang Li, Huiping Song

ISBN 978-88-95608-37-2; **ISSN** 2283-9216
DOI: 10.3303/CET1546182

Study on the Life Estimation of Civil Aviation Engine

Chungang Qu*, Hongbo Peng

College of Aeronautical Engineering, CAUC, Tianjin, 300300, China.
pqbird@sina.com

The Life Estimation is one of important areas in Engine research. Take-off EGTM is an important parameter to monitor Engine performance. The value of take-off EGTM is influence on Engine life greatly. Reducing EGT will help to extend Engine life on wing (LOW), thereby reducing operating costs. Aiming at aero-Engine condition monitoring, the definition of take-off EGT Margin is given, estimation methods and their application on Engine life estimation are discussed.

1. Introduction

EGT (Exhaust Gas Temperature) is one of important engine monitoring performance parameters in Engine cross sections. CFMI (2001) and Pratt & Whintey (2001) published some materials to introduce engine condition monitoring. Engine failure and performance degradation will be shown by EGT rising. Osborn, B. E. et al. (2007) estimated a trend in *EGT*. Weihua Yang (2000) introduced aero-Engine Modeling and fault Diagnosis in his PhD thesis. Xisen Wen (1997) also reported pattern recognition for engine failure. Engine life depends on take-off *EGT* Margin commonly. And its improvement will help extending Engine life on wing and reducing airline operating costs. İ Yılmaz. (2009) studied the relationship between *EGT* and operational parameters in cfm56-7b engines. Mercer C R et al. (2007) published fundamental technology development for gas-turbine Engine health management and Jaw L C (2005) introduced several advancements. Ilbas, M., Turkmen, M. (2012) and Zhifeng Ye, Jianguo Sun (2002) used neural Network to estimate *EGT*. Jin guang Song, Chunsheng Xu (2003) applied genetic algorithm and BP network for engine replace forecast. Guang-Bin Yu et al. (2013) proposed a support process vector model to predict EGT.

2. The collection of take-off data

As the take-off phase is critical in flight safety, the data is often acquired by the automatic data logging system. The collected data used for Engine condition monitoring based on take-off *EGT* Margin include: 1) Aircraft identification information; 2) Take off parameters in the time of peak *EGT*: *EGT*, N1 (or EPR), TAT, etc.; 3) Bleeding air status.

Different methods are used for different styles to judge the Peak *EGT* during take-off, such as CF6-80C2 (installed in the B747-400, B767-200, etc.) uses the record 40s after the flight speed reaches 100 Knots; CFM56-3 (installed in B737-300/400/500) uses records when the aircraft height reaches 90m or 9s after the front wheel leaves ground; CFM56-5C (installed in the A320 series, etc.) is recorded when the *EGT* reaches the maximum.

3. The definition of take-off EGT margin

In order to meet the need of aircraft performance, Engine is usually required to be able to provide a constant thrust at a certain temperature. In the following we take the GE Engine (with N1 reflects the thrust) as an example.

In Figure 1, the horizontal axis represents the *OAT* (outside air temperature), *Tcp* is the inflection point (corner point) temperature or the flat rating temperature (such as the flat rating temperature of CFM56 Engine is 30 $°C$). There are three curves in the figure: Thrust, N1 and *EGT*. We can see from the thrust curve that, when

Please cite this article as: Qu C.G., Peng H.B., 2015, Study on the life estimation of civil aviation engine, Chemical Engineering Transactions, 46, 1087-1092 DOI:10.3303/CET1546182

$OAT < Tcp$ Engine can produce a constant thrust, when $OAT > Tcp$, in order to prevent excessive of *EGT* during take-off, the thrust is usually reduced, Engine won't produce the full rated thrust.

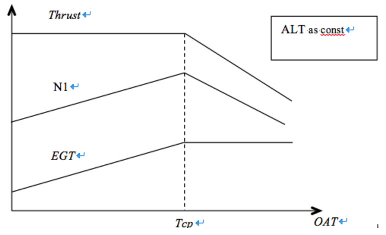

Figure 1: Schematic diagram of Engine flat thrust

It can be seen from the N1 Curve that, before a temperature reaches *Tcp*, with the increasing of *OAT*, speed N1 (setting value of N1 during take-off) is hoped to increase to keep Engine thrust maintain a constant; at a temperature above *Tcp*, in order to prevent excessive of *EGT*, engine will reduce the N1 take off setting, Correspondingly aircraft take-off commercial weight will be affected concerning the decreasing of thrust. It can be seen from the *EGT* curve that, at a temperature below *Tcp*, with the increasing of *OAT*, in order to keep Engine thrust constant, it is needed to increase N1, *EGT* will increase correspondingly; at a temperature above the *Tcp*, engine chooses sacrifice thrust to limit *EGT*.
Factors affecting take-off *EGT* include: the setting of take-off thrust, *OAT* (outside air temperature), outside air pressure and the Engine bleed air. When the aircraft take-off weight does not reach Maximum take off mass, the airlines usually require less thrust to use, that is don't let the Engine produce full-rated thrust, thus reduce the take-off *EGT* and extend Engine life.
Definition of Sea level take-off *EGT* Margin: the distance between *EGT* and *EGT* red value when the Engine produces full-rated thrust, at sea level, under flat rating temperature, with normal air-bleeding. As shown in Figure 2.

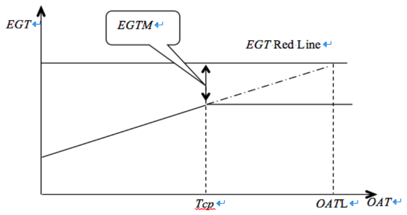

Figure 2: Schematic diagram of take-off EGT Margin

Take-off *EGT* Margin reflects the state of Engine performance. GE Engine also uses *OAT*L (outside air temperature limit) to reflect the Engine performance, as is shown in Figure 2. It indicates that at sea level, when the *OAT* reaches *OAT*L and the Engine produces full thrust, the *EGT* will reach *EGT* red line.
Figure 3 shows the effect of performance degradation on *EGT* Margin and *OAT*L. Curve 1 represents an Engine which just put to use, curves 2 represents an Engine whose performance has degraded. Figure 3 shows that with the degeneration of Engine performance, *EGTM* reduced, *OAT*L also reduced. So *EGTM* can reflect the general performance of the Engine.

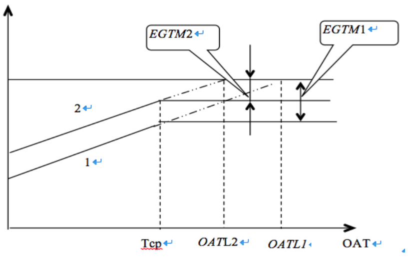

Figure 3: The effect of Engine performance degradation on EGM and OATL

4. The estimate of take-off EGT margin

There are a variety of methods for Take-off *EGTM* estimation, cruise ΔEGT is commonly used to estimate take-off *EGTM* in Engineering, in particular:

1) Estimate with test-stand *EGTM* in Engine factory and the change of ΔEGT during cruise phrase, see formula 1;

2) Estimate with the Engine ΔEGT alert during cruise, as shown in Equation 2.

$$EGTM_C = EGTM_{TESTCELL} - (\Delta EGT_C - \Delta EGT_I) \quad (1)$$

$$EGTM_C = \Delta EGT_{ALERT} - \Delta EGT_C \quad (2)$$

In which, $EGTM_C$ indicates the current Engine *EGTM*, $EGTM_{TESTCELL}$ as *EGTM* in factory units, ΔEGT_C as the deviation between current *EGT* and baseline, ΔEGT_I as deviation of the initial installed Engine *EGT* relative to baseline; ΔEGT_{ALERT} as the alert value of ΔEGT. When the *EGTM* difference between these two methods is within the range of 5 $°C$, it is thought the basic accuracy of the estimate have acquired.

Establishment method of the Engine cruise alert value is shown in Figure 4. Figure 4 indicates the relationship between test-stand *EGTM* and initial installed deviation ΔEGT_I of the PW4056, it can be seen that when *EGTM* reaches zero, $\Delta EGT = 22°C$. Therefore ΔEGT_{ALERT} of PW4056 Engine is defined as 22 $°C$.

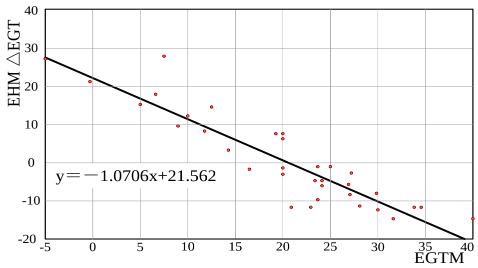

Figure 4: Determination of the cruise ΔEGT *alert value*

Finally, we must make it clear that the take-off *EGTM* equals 0 $°C$ only means that the Engine *EGT* will be reach the red line value when the Engine take-off full-thrust in at the sea level and flat rating temperature. If the Engine is arranged to take-off at low temperatures airport, or reduced thrust take off, *EGT* won't go over the red line.

The Engine users can take the following measures to increase *EGT* Margin:

1) If possible use reduced thrust take off;

2) Control the aircraft take-off weight, reduce unnecessary carrying fuel and water and use APU to supply air for air condition system to reduce the Engine load during the plane take-off, etc.

3) Cleaning the Engine gas path regularly can get a certain *EGT* Margin recovery.

4) Plan the route structures reasonably, such as arranging degraded Engine to fly some lines of the cold regions and so on.

5. The engine life estimation using take-off EGT margin

Currently, on condition maintenance is widely used for civil aviation Engine. It usually has only a soft limit for the whole Engine, and there are not strict working hours or the number of limit cycles. However, some parts such as turbine disks, shafts and seals, etc. have critical time restrictions, so they are known as LLP (life limited part). Failure of Engine System can usually be solved in the way of repair/replacement. After the failure is removed, the Engine can be used continuity. The Engine whose performance has completely degraded must return to factory to do performance recovery work. Engine performance status is evaluated mainly through condition monitoring, especially monitoring software. In Engineering, usually take-off *EGTM* is directly used to predict the Engine remaining life, to be outlined below.

After Installed in the aircraft, the cruise ΔEGT of Engine will increase gradually, rapidly in the early, slow down later. The rate of Engine *EGT* decline (i.e., the amount of decline per one thousand circulations) is defined as,

$$EGTDecay = \Delta EGT/(CSI/1000) \quad (3)$$

CSI represent cycles since installation. The relationship between flight cycles and Engine *EGT* rate of decline of a PW4000-94 inch Engine is shown in Figure 5. It can be seen that the *EGT* decline rate falls faster before2000 CSI, while it slows down after 2000CSI.
For the remaining life prediction of Engine on the wing, in Engineering, the Engine take-off *EGTM* is estimated at first, then predicted using the CSI and *EGT* decline rate. Here we give an example of the residual life prediction of Engine.

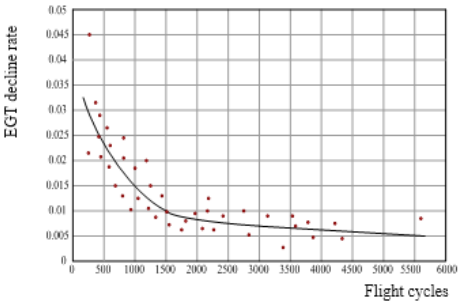

Figure 5: The relationship between Engine EGT decline rate and the flight cycles for PW4000-94

Example 1: When *EGTM* is less than *EGTDecay*
Known: the time and cycles of a PW4056 Engine since installation are
TSI / CSI = 1200Hrs/494Cycles
The EGTM in test-stand before installation $EGTM_{TESTCELL} = 12°C$
The initial value after installation $\Delta EGT_I = 8°C$, the current moment $\Delta EGT = 15°C$
PW4056 Engine $\Delta EGT_{ALERT} = 22°C$
1) Estimate *EGTM*
Estimate using test-stand *EGTM* and cruise ΔEGT increment

$$EGTM_C = EGTM_{TESTCELL} - (\Delta EGT_C - \Delta EGT_I) = 12 - (15 - 8) = 5°C$$

Estimate using ΔEGT alert Value

$$EGTM_C = \Delta EGT_{ALERT} - \Delta EGT_C = 22 - 15 = 7°C$$

The error of the two estimation method is within the prescribed limits, take the mean value $EGTM_C = 6°C$
2) Predict the remaining life
The currently CSI of the Engine is only 494Cycs, thus, the decline rate is:

$$EGTDecay = \Delta EGT/(CSI/1000) = 7/(494/1000) = 14.17(°C/1000Cycles)$$

Considering that the current decline rate of *EGT* is large and *EGTM* is little, the Engine doesn't need to be regarded as time-phased process. After investigation, the utilization rate of the aircraft installed with the Engines is 2.12 cycles / day. Thus, the theoretical remaining time before *EGTM* reaches zero is:

$$Cycle_{\mathrm{Re}maining} = (EGTM_C / EGTDecay) \times 1000 = (6/14.17) \times 1000 = 423(Cycles)$$

$$Life_{\mathrm{Re}maining} = (Cycle_{\mathrm{Re}maining}/2.12)/7 = (423/2.12)/7 = 28.5(Weeks)$$

$Cycle_{\mathrm{Re}maining}$ is the remaining number of cycles, $Life_{\mathrm{Re}maining}$ is the remaining life (unit: week).
So the Engine *EGTM* is expected to reach zero 28.5 weeks later.
Authentication: The theoretical zero *EGTM* remaining cycle of the Engine is 423Cycles. After the Engine is removed, the test-stand *EGTM* is -1 °C , and the total CSI is 935Cycles, thus it was used 935-494 = 441

Cycles after the predicted point. The theoretical zero *EGTM* remaining cycles and the actual number of cycles of the Engine are basically the same.
Example 2: When *EGTM* of is more than *EGTDecay*
Known: the time and cycles of a PW4056-3 Engine since overhaul are
TSO / CSO = 6939H/3241C
The *EGTM* in test-stand before Installation $EGTM_{TESTCELL} = 48°C$
The initial value after installation $\Delta EGT_I = 6°C$, the current moment $\Delta EGT = 34°C$
PW4056-3 Engine $\Delta EGT_{ALERT} = 56°C$
1) Estimate *EGTM*
Estimate using test-stand *EGTM* and cruise ΔEGT increment

$$EGTM_C = EGTM_{TESTCELL} - (\Delta EGT_C - \Delta EGT_I) = 48 - (34 - 6) = 20°C$$

Estimate using ΔEGT alert Value

$$EGTM_C = \Delta EGT_{ALERT} - \Delta EGT_C = 56°C - 34°C = 22°C$$

The error of two estimation method is within the prescribed limits, take the mean value $EGTM_C = 21°C$
2) Estimation the remaining life
The average *EGT* decline rate of the Engine is:

$$EGTDecay = \Delta EGT / (CSI / 1000) = 28 / (3241 / 1000) = 8.64(°C / 1000 Cycles)$$

The Engine CSI has reached 3241Cyces, and *EGT* Margin is more than *EGTDecay*, time-phased process should be used. The change of *EGT* decline rate is as following:
0-1064 cycles:

$$EGTDecay = \Delta EGT / (CSI / 1000) = 12 / (1064 / 1000) = 11.28(°C / 1000 Cycles)$$

1064-2103 cycles:

$$EGTDecay = \Delta EGT / (CSI / 1000) = 8.6 / (1039 / 1000) = 8.28(°C / 1000 Cycles)$$

2103-3241 cycles:

$$EGTDecay = \Delta EGT / (CSI / 1000) = 7.4 / (1138 / 1000) = 6.5(°C / 1000 Cycles)$$

As can be seen from the above data, there is large deviation between the average Engine *EGT* decline rate and the *EGT* decline rate during each time stage. It will have a greater error if the average decline rate is used to predict the remaining life.
As Engine is normal recession mode, the replace time of the Engine may be thereby be calculated using the decline rate 6.50 $°C \ / 1000$ Cycles after the 3000 cycles. After investigation, the utilization rate of the aircraft installed with the Engines is 2.67 cycles / day.
Thus, the theoretical remaining time before Engine *EGTM* reaches zero is:

$$Cycle_{Remaining} = (EGTM_C / EGTDecay) \times 1000 = (21/6.5) \times 1000 = 3231(Cycles)$$

$$Life_{Remaining} = \left(Cycle_{Remaining} / 2.12\right) / 7 = (3231/2.67) / 7 = 173(Weeks)$$

So, EGTM is expected to reach zero after 173 weeks. The time can only serve as a reference of the Engine replacement time currently.
Over time, the calculation should continue with time goes, until the *EGTM* is less than *EGTDecay* when the method in example 1 should be used for prediction.

6. Conclusions

Take-off EGT Margin has a quite big influence on Engine life. Improvement in take-off *EGT* Margin will help to extend Engine on-wing time, and to reduce operating costs. Here we have analyzed and discussed the civil aviation Engine life prediction based on take-off *EGT* Margin.

Associated with relative monitoring software, Engine performance monitoring can, on one hand, help maintenance technician to troubleshoot, on the other hand, Engineers can use long-term changes of Engine performance to manage Engine fleet effectively, such as arranging Engine removal in echelon, planning workscope of Engine overhaul, et.al.

Acknowledgements

This work was financially supported by Civil Aviation University of China research fund: ZXH2012P007.

References

GE Aircraft Engine / CFMI, 2001, Engine condition monitoring, USA, GEAE / CFMI.

Hao Y., 2004, Engine Take-off EGT Margin Estimates, Aviation Maintenance and Engineering, (2): 39-40.

Hao Y., Sun J.G., Bai J., 2003, The status and prospects of aviation gas turbine engine gas path fault diagnosis, Journal of Aerospace Power, 18: 753-760.

Ilbas M., & Turkmen M., 2012, Estimation of exhaust gas temperature using artificial neural network in turbofan engines, Isi Bilimi Ve Teknigi Dergisi.

Jaw L.C., 2005, Recent advancements in aircraft engine health management technologies and recommendations for the next step, ASME GT 2005 -68625.

Mercer C.R., Simon D.L., Hunter G.W., 2007, Fundamental technology development for Gas-Turbine Engine health management, NASA-20070022364.

Osborn B.E., Fullington M.D., Herron W.L., Hershey J.E., Dockendorff J.E., Hansen C.H., (2007), System and method for estimating a trend in exhaust gas temperatures in a turbine engine. EP doi: EP1746271 A2.

Pratt & Whintey, 2001, Engine health monitoring (EHM) training guide, USA, Pratt & Whintey Customer Training Center.

Song J.G., Xu C.S., 2003, Engines replace forecast based on genetic algorithm and BP network, Journal of Aerospace Power, (5): 676-680.

Wen X.S., 1997, Pattern Recognition and Status Monitoring [M], Changsha: National University of Defense Technology Press.

Xu C.S., 2000, The Reliability of Aviation Engines Concluding Report, Civil Aviation University of China.

Yang W.H., 2000, Aero-Engine modeling and fault diagnosis [PhD thesis], Nanjing, Nanjing University of Aeronautics and Astronautics.

Ye Z.F., Sun J.G., 2002, Application prospect of using neural network in aircraft engine gas path fault diagnosis, Journal of Propulsion Technology, 01(1): 1-4.

Yılmaz I., 2009, Evaluation of the relationship between exhaust gas temperature and operational parameters in cfm56-7b engines. Proceedings of the Institution of Mechanical Engineers Part G Journal of Aerospace Engineering, 223, 433-440.

Yu G.B., Ding G., Yao W., Huang L., 2013, Aeroengine exhaust gas temperature prediction using support process vector machine, Electric Machines & Control.