Abstract - Modern digital engine monitors with separate probes for each cylinder provide useful diagnostic information that precedes large class of engine problems. Limits for alarm alerts in such monitors are set to encompass all phases of engine operation. Method for monitoring engine parameters that considers multiple engine regimes corresponding to a current flight phase (engine run-up, taxi, take-off, climb, cruise and descent) and individual cylinder differences is proposed. Engine operation is presented graphically on the engine monitor display as patterns consisting of CHT/EGT bars. They can be compared to previously stored patterns corresponding to a particular flight phase possibly indicating deviations from previous flights. Flight phases are determined from engine RPM parameter together with speed and vertical speed derived from geometric altitude present in GPS data.

I. INTRODUCTION

Most of general aviation aircrafts (popularly known as small private airplanes) with the exception of turboprop and business jet aircrafts are powered by gasoline (Avgas) piston engines. Piston engine is a heat engine designed to convert energy contained in fuel into mechanical energy. It uses reciprocating pistons to convert pressure into a rotating motion. Aircraft piston engine is not very efficient at converting energy contained in a fuel to a physical motion. Only about one third of energy from fuel is converted to mechanical energy, [1]. Monitoring of engine temperatures make it possible to assess the efficiency of combustion process and indirectly detect most of engine problems, [2]. The main source of engine information traditionally available to pilot are several traditional gauges indicating cylinder head temperature (CHT), exhaust gas temperature (EGT), engine rotational speed (RPM, tachometer), fuel flow, oil temperature and oil pressure, [1,3]. These classical gauges give very basic information about engine condition. A single CHT and EGT gauge gives an average of each cylinder’s head and exhaust gas temperature. Graphic engine monitor, [3-6], replaces this older method of viewing of one temperature with precise multi-cylinder engine monitoring of EGT and CHT temperatures plus myriad of other parameters. Piston engines used in general aviation aircrafts have a MTBF (considering total loss of power) in a range of 5000-30000 hours depending on engine complexity, operation and maintenance. With monitoring of engine parameters it is possible to detect impending engine problems and increase engine operational reliability. Engine monitors usually have one set of parameter limits for all flight phases that when exceeded issue an alarm. Introduction of separate parameter limits for various flight phases may improve fault detection capability of engine monitor.
TABLE I. MONITORED ENGINE PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGT</td>
<td>Exhaust Gas Temperature</td>
</tr>
<tr>
<td>CHT</td>
<td>Cylinder Head temperature</td>
</tr>
<tr>
<td>OIL TEMP</td>
<td>Oil Temperature</td>
</tr>
<tr>
<td>OIL PRES</td>
<td>Oil Pressure</td>
</tr>
<tr>
<td>TIT 1</td>
<td>Turbine Inlet Temperature</td>
</tr>
<tr>
<td>TIT 2</td>
<td>Turbine Inlet Temperature</td>
</tr>
<tr>
<td>OAT</td>
<td>Outside Air Temperature</td>
</tr>
<tr>
<td>CDT</td>
<td>Compressor Discharge Temperature</td>
</tr>
<tr>
<td>IAT</td>
<td>Intercooler Air Temperature</td>
</tr>
<tr>
<td>CRB</td>
<td>Carburetor Air Temperature</td>
</tr>
<tr>
<td>CDT - IAT</td>
<td>Intercooler cooling</td>
</tr>
<tr>
<td>RPM</td>
<td>Rotations Per Minute</td>
</tr>
<tr>
<td>MAP</td>
<td>Manifold Pressure</td>
</tr>
<tr>
<td>% HP</td>
<td>% Horse Power</td>
</tr>
<tr>
<td>CTD</td>
<td>CHT Cooling Rate</td>
</tr>
<tr>
<td>DIF</td>
<td>EGT Span</td>
</tr>
<tr>
<td>FF</td>
<td>Fuel Flow</td>
</tr>
</tbody>
</table>

'Monitor, #fastest cooling cylinder, #difference between the hottest and coolest EGT

Monitored engine parameters (available in JPI EDM 830) are shown in Table I. The similar set of parameters is also available in other modern engine monitors. Engine monitor automatically records engine parameters during each flight into a log, Fig. 5. New log record is typically recorded every 6 seconds giving 600 records per hour. Recorded data can be downloaded with cable, wireless connection or memory card for later analysis using software, [7], installed on a PC for sophisticated graphical analysis. Suspicous data logs can be sent to a mechanic or engine manufacturer for further clarification.

III. ENGINE PARAMETERS STATISTICS

Graphical representations of the probability distributions of key engine parameters CHT, EGT and TIT in form of frequency histograms are shown in Figs. 6-8, [8]. As can be seen in figures, the probability distributions have several peaks and as such are too complicated for simple application of common mathematical distributions. One solution to this problem is use of the statistical summary in form of percentiles, [8,9]. Percentile is the value of a variable below which a certain percent of observations fall. The 99\textsuperscript{th} percentile is the value below which 99% of the observations may be found. Statistical analysis was performed on three engine log files supplied with the EzTrends2 software, [7], Flt#49 of duration 2.57 hours, Flt#56 of duration 0.43 hours and Flt#61 of duration 0.45 hours, belonging to a six cylinder, 280 HP turbonormalized Continental engine TSIO-550-G, from 2007 Mooney M20TN Acclaim aircraft, N257TM, with no known faults present. Resulting statistical summary of engine parameters encompassing all engine regimes is shown in form of Box-Wiskers plots in Fig. 9 with corresponding data given in Table II. Engine operation during a whole flight could be additionally summarized with flight summary generated by EzTrends2 software (average, max, min value of engine parameters) as shown in Fig. 10. Temperature deviations form average (see color legend) for each cylinder are shown in small picture. As can be seen, extreme values (minimums and maximums) of engine parameters during normal operation for the period of whole flight, shown in Table II and Fig. 10, are

Figure 5. Example from engine monitor log, include engine parameters and GPS data

Figure 6. EGT 1 histogram

Figure 7. CHT1 histogram

Figure 8. TIT 1 histogram

Figure 9. EGT1-6, TIT1, TIT2, CHT1-6 and OILT for all engine operating regimes
TABLE II. STATISTICAL SUMMARY OF SELECTED ENGINE PARAMETERS (TEMPERATURES) ENCOMPASSING ALL ENGINE REGIMES (LIMITS USEFUL FOR ALERTS ARE SHIFIED)

<table>
<thead>
<tr>
<th>Param.</th>
<th>μ</th>
<th>Std.Dev.</th>
<th>Min</th>
<th>Max</th>
<th>Pi</th>
<th>P99</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGT1</td>
<td>1447.5</td>
<td>143.9</td>
<td>956</td>
<td>1595</td>
<td>1036.6</td>
<td>1586</td>
</tr>
<tr>
<td>EGT2</td>
<td>1446.8</td>
<td>149.0</td>
<td>796</td>
<td>1608</td>
<td>897</td>
<td>1576.2</td>
</tr>
<tr>
<td>EGT3</td>
<td>1451.3</td>
<td>148.0</td>
<td>813</td>
<td>1610</td>
<td>972</td>
<td>1586.2</td>
</tr>
<tr>
<td>EGT4</td>
<td>1441.4</td>
<td>150.6</td>
<td>751</td>
<td>1599</td>
<td>912.8</td>
<td>1577</td>
</tr>
<tr>
<td>EGT5</td>
<td>1443.3</td>
<td>118.6</td>
<td>843</td>
<td>1580</td>
<td>1069</td>
<td>1556</td>
</tr>
<tr>
<td>EGT6</td>
<td>1422.2</td>
<td>134.6</td>
<td>604</td>
<td>1564</td>
<td>829.2</td>
<td>1542.2</td>
</tr>
<tr>
<td>TIT1</td>
<td>1430.7</td>
<td>179.1</td>
<td>739</td>
<td>1655</td>
<td>966</td>
<td>1656</td>
</tr>
<tr>
<td>TIT2</td>
<td>1494.4</td>
<td>177.5</td>
<td>876</td>
<td>1679</td>
<td>837</td>
<td>1588.2</td>
</tr>
<tr>
<td>CHT1</td>
<td>308.3</td>
<td>31.1</td>
<td>179</td>
<td>352</td>
<td>209</td>
<td>345</td>
</tr>
<tr>
<td>CHT2</td>
<td>306.2</td>
<td>31.8</td>
<td>172</td>
<td>371</td>
<td>207.6</td>
<td>335.2</td>
</tr>
<tr>
<td>CHT3</td>
<td>290.0</td>
<td>28.0</td>
<td>173</td>
<td>349</td>
<td>196.4</td>
<td>335.2</td>
</tr>
<tr>
<td>CHT4</td>
<td>292.0</td>
<td>27.7</td>
<td>191</td>
<td>345</td>
<td>201</td>
<td>342</td>
</tr>
<tr>
<td>CHT5</td>
<td>296.0</td>
<td>27.5</td>
<td>190</td>
<td>372</td>
<td>209.6</td>
<td>349</td>
</tr>
<tr>
<td>CHT6</td>
<td>299.4</td>
<td>29.9</td>
<td>188</td>
<td>365</td>
<td>206</td>
<td>350.2</td>
</tr>
<tr>
<td>OILT</td>
<td>166.7</td>
<td>7.43</td>
<td>123</td>
<td>181</td>
<td>137</td>
<td>181</td>
</tr>
</tbody>
</table>

Figure 10. Flight summary as generated by EzTrends2 software

TABLE III. DEFAULT ENGINE MONITOR ALARM LIMITS

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Default Low Limit</th>
<th>Default High Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHT1</td>
<td>450 °F 230 °C</td>
<td></td>
</tr>
<tr>
<td>EGT1</td>
<td>1550 °F 843 °C</td>
<td></td>
</tr>
<tr>
<td>OILT</td>
<td>90 °F 32 °C</td>
<td>230 °F 110 °C</td>
</tr>
<tr>
<td>TIT1</td>
<td>1650 °F 900 °C</td>
<td></td>
</tr>
<tr>
<td>CLD</td>
<td>-60 °F/min -33 °C/’C/min</td>
<td></td>
</tr>
<tr>
<td>DIF</td>
<td>500 °F 280 °C</td>
<td></td>
</tr>
</tbody>
</table>

Figure 11. Figure Speed, altitude, RPM combinations during a flight

```
\[ r = \frac{100\text{RPM}}{20\text{RPM}_\text{MAX}} \] (1)
```

B. Calculated Percent of HP - %HP

Same RPM has different meaning in term of engine load during climb, cruise and descent. Relation between the speed, altitude and RPM is shown in Fig. 11. High RPM is present both in climb and cruise. Engine load is generally much greater during a climb. Example of regime switching variable \( r \) that separates operating regimes in 20% RPM brackets is defined by (1), where \( \text{RPM}_\text{MAX} \) is maximal value RPM can achieve (~2850).

```
\[ r = \frac{\%\text{HP}}{20} \] (2)
```

Figure 12. % HP as a function of RPM and MAP (manifold pressure)
C. Flight Phase

Full glass cockpit is still rare in general aviation aircraft. However, GPS receiver is commonly available. Many engine monitors can accept GPS data, Fig. 13. By incorporating GPS speed, GPS geometric altitude and calculated vertical speed to engine monitor RPM parameter it is possible to determine actual flight phase.

The engine is under different load in climb, cruise and descent that sometimes can’t be distinguished from engine parameters alone. The use of speed, vertical speed and engine RPM enables distinguishing of climb, cruise and descent phase. Vertical speed is determined from successive altitudes data $Alt_{t_1}$ and $Alt_{t_2}$ at $t_1$ and $t_{t_1}$, (3).

$$V_S = \frac{Alt_{t_2} - Alt_{t_1}}{t_{t_1} - t_1} \quad (3)$$

GPS speed is a groundspeed and in presence of very strong winds may vary significantly from indicated speed (IAS). It would be better if one could get IAS once the aircraft is aloft. Flight phase dependent regimes are particular suitable because most engine monitor documentation and literature describe potential problems in relation to the specific phase of a flight (e.g. “compare temperatures to past climbs”) with readily available recommendations about engine operation and corrective actions, [2,5,6]. Speed, altitude and vertical speed during one flight are shown in Figs. 14-16.

D. Rules for Flight Phase Determination

Following flight phases are chosen: engine run-up, take-off, climb, cruise, descent. Landing is not included due to the short duration and low RPM that is not hard on the engine. Rules for the determination of the flight phase are given below (SPEED is GPS groundspeed, VS is calculated vertical speed from successive readings of GPS altitude and RPM is engine rotation speed):

- IF $SPEED < 3$ AND $800 < RPM < 1700$  
  Engine run-up
- IF $3 < SPEED < 20$ AND $30 < VS = 30$ AND $RPM < 1500$  
  Taxi
- IF $3 < SPEED < 45$ AND $30 < VS = 30$ AND $RPM > 2300$  
  Take-off
- IF $SPEED > 45$ AND $VS >200$ AND $RPM > 2000$  
  Climb
- IF $SPEED > 45$ AND $-200 < VS < 200$  
  Cruise
- IF $SPEED > 45$ AND $VS < -200$  
  Descent

Recommended values for run-up are bellow 1500, value of 1700 is set after analyzing available logs. In real world small margin of error (e.g. 30 ft/min due to GPS altitude error) must be allowed around value of 0 valid for ideal case, Compromise value to allow for strong headwinds

With previously defined rules very small percentage of time engine parameters will not be labeled to any flight phase (≈1.5%). Disadvantage of such determination of flight phases is that it depends on availability of GPS signal. Under some rare occasions GPS data may be temporary unavailable and in that case only warning alerts not related to flight phase may be issued.

V. FLIGHT PHASE REGIME DEPENDENT STATISTICS

Statistical summaries for six previously defined engine regimes are shown in Figs. 17-22 and Table V. Please note that graphs vary in temperature scales (different temperature scale than used for all regimes shown in Fig. 9) and parameter spreads are smaller.

![Graph](image-url)

Figure 17. EGT1-6, TIT1, TIT2, CHT1-6 and OILT for engine run-up

![Graph](image-url)

Figure 18. EGT1-6, TIT1, TIT2, CHT1-6 and OILT for taxi

![Graph](image-url)

Figure 19. EGT1-6, TIT1, TIT2, CHT1-6 and OILT for take-off

![Graph](image-url)

Figure 20. EGT1-6, TIT1, TIT2, CHT1-6 and OILT for climb
VI. Flight Phase Prototype Patterns

Within the engine there exist small temperature differences between cylinders due to cylinder position (different air cooling), differences in distance traveled by the air from the intake and differences among injectors. This can be seen as slightly different bar heights belonging to various cylinders. Differences also exist with the change of flight phase. It may be beneficial to compare current pattern with previously stored prototype pattern corresponding to that particular flight phase.

A. Pattern Vector

Pattern vector \( v_i \) consist of components \( E_i \) and \( C_i \) that are EGT and CHT values for cylinder \( i \) at some record, \( N_c \) is the number of cylinders, (4).

\[
v_i = [E_i, \ldots, E_{N_c}, C_i, \ldots, C_{N_c}]
\]  

B. Pattern Vector Normalization

To later facilitate better pattern comparison pattern normalization is performed, removing some influence of temperature differences within a flight phase to a shape of the pattern. Normalization is performed by determining highest EGT among all cylinders, \( E_{\text{MAX}} \) (5). EGT and CGT values are then divided by \( E_{\text{MAX}} \).

\[
E_{\text{MAX}} = \max(E_i) \quad i=1, \ldots, N_c
\]  

Normalized EGT values, \( E_{N,i} \) are, (6):

\[
E_{N,i} = \frac{E_i}{E_{\text{MAX}}} \quad i=1, \ldots, N_c
\]  

Similarly, normalized CHT values, \( C_{N,i} \) are, (7):

\[
C_{N,i} = \frac{C_i}{C_{\text{MAX}}} \quad i=1, \ldots, N_c
\]  

All components are within the interval [0, 1], (8),(9):

\[
0 \leq E_{N,i} < 1 \quad i=1, \ldots, N_c
\]  

\[
0 \leq C_{N,i} < 1 \quad i=1, \ldots, N_c
\]  

Normalized test pattern is now vector \( v_{N,r} \) (10).

C. Prototype Pattern Vector

Prototype pattern vector for flight phase \( r \) is the vector \( v_{N,r} \) (11), that consists of averaged normalized values \( E_{N,i,r} \) and \( C_{N,i,r} \) determined by (12) and (13).

\[
v_{N,r} = [\hat{E}_{N,i,r}, \ldots, \hat{E}_{N,i}, \hat{C}_{N,i,r}, \ldots, \hat{C}_{N,i}] \]  

\[
\hat{E}_{N,i,r} = \frac{1}{N_r} \sum_{k=1}^{N_r} E_{N,i,r,k} \]  

\[
\hat{C}_{N,i,r} = \frac{1}{N_r} \sum_{k=1}^{N_r} C_{N,i,r,k}
\]  

where \( E_{N,i,r,k} \) and \( C_{N,i,r,k} \) are EGT and CHT values of \( k^{th} \) record and \( N_r \) is the total number of records for the flight phase \( r \). Components of normalized prototype vectors for each of six flight phases are shown in Table VI.

VI. Method for Fault Detection

Previous statistics and temperature profiles for each flight phase can be integrated in a fault detection method as illustrated in Fig. 23. Limit checkers may be applied to measured engine parameters, [10].

A. Limit Checkers for Global Limits

Limit checkers can be applied using engine parameters limits extracted from engine logs that encompass whole flights and are suitable for detection of severe engine problems issuing a warning alert, (14):

\[
L_{x,i} < p_i < L_{y,i}
\]  

where

\[
L_{L,i} \quad \text{is low limit for parameter } p_i
\]

\[
L_{H,i} \quad \text{is high limit for parameter } p_i
\]

\[
p_i \quad \text{is engine parameter } i
\]

B. Limit Checkers for Regime Dependent Limits

Same technique can also be applied to engine regime dependent limits, (15). This places narrower limits to engine parameters corresponding to a particular engine regime and is suitable for detection of smaller problems.
Such limits are beneficial as it may be of interest to detect smaller problems (issuing less severe caution alerts).

\[ L_{L,r} < P_i < L_{H,r} \]

where

\[ L_{L,r} \] is low limit for regime \( r \)
\[ L_{H,r} \] is high limit for regime \( r \)

Percentiles from Table V can be used for setting limits.

C. Limit Checkers for Detection of Pattern Deviations

The Euclidian distance between vector of engine parameters represented in normalized engine pattern and stored normalized prototype pattern corresponding to current flight phase is determined. For vectors \( p \) and \( q \) the Euclidian distance is given by (16).

\[ d(p,q) = \sqrt{(p_1 - q_1)^2 + (p_2 - q_2)^2 + ... + (p_n - q_n)^2} \]

Considering variance for EGTs and CHTs, \( \sigma^2_E \) and \( \sigma^2_C \), weighted Euclidian distance between test vector \( v_{T,r} \) and prototype vector \( v_{P,r} \) is given by (17). Typical values for variances (cruse) are \( \sigma^2_E = 0.00025 \) and \( \sigma^2_C = 0.000025 \).

\[ d_{T,P,r} = \frac{1}{\sigma^2_E} \sum_{i=1}^{n}(T_{i,r} - P_{i,r})^2 + \frac{1}{\sigma^2_C} \sum_{i=1}^{n}(C_{i,r} - P_{i,r})^2 \]

Distribution of distances \( d_{T,P,r} \) from all test patterns to prototype pattern for each regime \( r \) is shown in Fig. 24. Statistical summary of distance between prototype and patterns from the same regime are given in Table VII.

VIII. Conclusion

The graphic engine monitor is a tool for engine management that contributes to proactive maintenance. Exploiting statistical properties of engine parameters may be useful when devising acceptable parameter limits for fault detection. Statistical summary of engine parameters in forms of percentiles can be used for describing complex empirical distributions in a simple way. One fits all statistic of engine parameters acquired by analyzing the whole engine log is suitable for devising wide parameter limits for warning (severe) alert. For detection of smaller problems more precise engine parameter limits are needed that are related to a particular engine operating regime. Combining engine RPM with the additional GPS data, actual flight phase can be determined and used for separation of engine operation into regime corresponding to a flight phase. Within a particular regime engine parameters can be compared to much narrower limits, that if exceeded issue caution (less severe) alert. Use of flight phase for regime determination has an advantage of documented engine parameter values that are expected in various phases of flight. Temperature profile comparison with stored profiles (patterns) for each flight phase is included for addition detection of temperature anomalies. Percentile limits are often too sensitive for detection of potential faults; hence permitted number of threshold exceedances within a specific time period may be introduced to achieve desired fault detection sensitivity.

REFERENCES


Table VII: Statistical Summary: Distances from Prototype

<table>
<thead>
<tr>
<th>Regime</th>
<th>Mean µ</th>
<th>Std. Dev. σ</th>
<th>Min</th>
<th>Max</th>
<th>P1</th>
<th>P99</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-up</td>
<td>20.8972</td>
<td>11.07503</td>
<td>4.80124</td>
<td>50.67822</td>
<td>5.2941</td>
<td>54.87564</td>
</tr>
<tr>
<td>Climb</td>
<td>20.49501</td>
<td>11.62248</td>
<td>1.69166</td>
<td>65.63849</td>
<td>3.2465</td>
<td>92.11229</td>
</tr>
<tr>
<td>Cruise</td>
<td>9.55232</td>
<td>10.01092</td>
<td>2.80137</td>
<td>56.67822</td>
<td>2.95024</td>
<td>92.11229</td>
</tr>
</tbody>
</table>

*Shaded values for P99 can be used for limits

Limit checker can be applied to distance as well, (18).

\[ d_i < L_{H,r} \]

If distance is greater than 99th percentile limit caution is issued. This indicates that shape of a current pattern is too different from the stored prototype for a flight phase.

D. Percentiles and Detection Sensitivity

Failures in many technical systems follow a risk pyramid illustrated in Fig. 25.[8] General idea behind this figure is that in a large sample number of minor events precede more severe and very severe events. Percentiles are fixed to 1% and 99% values, and this sensitivity may be set too high even for the smallest engine problems. Considering just upper limits of engine parameters (99th percentiles), 600 records of engine parameter per hour would translate to average of 6 caution alerts per hour.

Figure 25. Pyramidal relationship of risk, tailored to engine problems

Figure 26. Permitted number of threshold exceedances within a specified time frame

for each parameter, or 72 caution alerts for all EGT and CHT values in 6 cylinder engine. To adjust the sensitivity of detection one may additionally specify the number of limit exceedances per time period (use of counter) that should be reason for concern (e.g. more than 5 exceedances per parameter in last 5 minutes). This number is adjusted to necessary fault detection sensitivity (fine tuning). Forgetting factor is needed (e.g. in form of resetting fault counter after a period of time). Combining thresholds and the number of threshold exceedances within specified time frame, Fig. 26, distinguishing between sporadic and frequent events, appropriate sensitivity could be achieved.