Abstract - Digital engine monitor can record vast amount of data in form of engine parameters from the aircraft piston engine. By analyzing these parameters it should be possible to detect majority of current or impending engine problems. Statistical description of engine parameters together with rule based pattern recognition of catalogued graphic engine fault patterns shown as bar graphs on the engine monitor display may help detect abnormal engine conditions. Method for automatic analysis of engine monitor data and labeling potential problems is described.

I. INTRODUCTION

Almost all general aviation aircrafts (with the exception of business jets) are powered by engine–propeller combination. In most single-engine light aircraft, the power plant is a four-stroke reciprocating engine with a direct drive to a propeller. Aircraft piston engines are relatively reliable devices. Engine failures are rare, but do happen. In case of engine failure it is possible to land an aircraft, but this is very risky event, particularly if engine failure happen over inhospitable terrain, in IFR (instrumental) conditions or at night.

II. PISTON ENGINE AND PROPELLER COMBINATION

A. Piston Engine

Piston engine is an economical source of power for small (general aviation) aircraft due to its power output, price and fuel consumption at cruise speed of a typical general aviation aircraft. Essentially it is a heat engine that uses one or more reciprocating pistons to convert pressure into a rotating motion. Most common aircraft piston engine are horizontally opposed, air-cooled four-, six- and eight-cylinder engines. Engines have old fashioned but reliable fixed timed dual magneto ignition systems (no use of electronics).

B. Propeller

Propellers are generally directly driven by an engine, although gearbox speed reducers exist on some higher power engines. Most training aircraft employ fixed-pitch propeller while complex aircrafts and trainers use constant speed propeller. Constant speed propeller is necessary to cope efficiently with this with variations in speed range and engine power. As aircraft speed increases, so does propeller efficiency, up to a peak. However, at faster speeds, efficiency reduces. By varying the pitch, it is possible to extend this maximum efficiency over a greater speed range. Also, as airplane climb higher, the density of the air decreases. To maintain speed, a coarser blade angle must be taken.

C. Engine-Propeller Power Management

Aircraft engine-propeller combination (with constant speed propeller) is controlled by three levers: thrust, propeller pitch and mixture. Thrust controls manifold pressure (MAP), propeller pitch controls RPM (revolutions per minute) and mixture controls fuel pressure and indirectly fuel flow. Manifold pressure (MAP) is the actual pressure in the inlet manifold in inches of mercury (Hg), measured by a sensor downstream of the throttle plate.

III. ENGINE MONITOR

The main source of engine information available to pilot are several gauges indicating engine rotational speed (RPM, tachometer), oil pressure, oil temperature, exhaust gas temperature (EGT) and fuel flow. These gauges give very basic information about the engine condition. More advanced solutions exist today in form of engine monitors. Such engine monitors cover much more engine data then basic gauges in a cockpit (about dozen of parameters that are also recorded and can be analyzed later), Fig. 1. Adequate skill is needed for correct engine monitor data interpretation. Beside engine condition monitoring, these engine monitors can be used for improved engine operation (fuel economy). Piston engine is not particularly efficient and only a small portion of the energy from combustion produces movement of the piston during the power stroke. The greatest part of energy passes into the exhaust pipe as hot gasses. By monitoring the temperature of exhaust gasses it is possible to assess the quality of the combustion process. Diminished efficiency of the

Figure 1. Engine monitor display (EDM 830)
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 1</td>
</tr>
<tr>
<td>OIL PRES</td>
<td>Oil Pressure 1</td>
</tr>
<tr>
<td>TIT 1</td>
<td>Turbine Inlet Temperature 1</td>
</tr>
<tr>
<td>TIT 2</td>
<td>Turbine Inlet Temperature 2</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>% HP</td>
<td>% Horse Power</td>
</tr>
<tr>
<td>CLD</td>
<td>CHT Cooling Rate 2</td>
</tr>
<tr>
<td>DIF</td>
<td>EGT Span</td>
</tr>
<tr>
<td>FF</td>
<td>Fuel Flow</td>
</tr>
</tbody>
</table>

*optional, *fastest cooling cylinder,* difference between the hottest and coolest EGT.*

combustion process that generates power indicates engine problems like low compression, non-uniform fuel distribution, faulty ignition, and clogged injectors, [1]. Engine parameters are collected from engine monitor probes installed on an engine. Engine monitor used in an experiment (EDM 830) records and calculates numerous engine parameters that are listed in Table I and shown in form of bar graph and digital display, Fig. 1. Parameters are displayed and recorded at the programmed interval (default setting is every 6 seconds). Depending on the monitored engine not all parameters are available. Other parameters (battery voltage, remaining fuel etc.) collected by the monitor are collected but are not relevant for consideration here. Example of engine monitor log is shown in Fig. 2. Graphical representation for main engine parameters through the duration of one whole flight is shown in Fig. 3 (upper curves represent EGTs and lower curves CHTs), [2]. Engine diagnosis charts supplied with the engine monitor describe engine fault patterns (shown in terms of bar graph on a display) can help diagnose various engine faults, [1]. There are 15 general patterns that indicate particular faults.

IV. METHOD FOR FAULT DETECTION

Proposed method is combination of statistical and pattern recognition approach. It preserves default engine monitor alarm limits but adds new alarm limits corresponding to current engine working regime and augments it all with rule based fault pattern recognition, Fig. 4. Method is intended for parsing engine parameters log after the flight. Great problem with advising fault detection method is due to very reliable aircraft engines. It is very difficult, with exception of large manufacturer and overhaul services, to obtain sufficient large sample of failed engines. On the other hand artificial failures can be produced (failure injection), but this process could harm the expensive engine (some failures would require destructive testing with high price tag), yet it will not cover all problems.

V. STATISTICS OF ENGINE PARAMETERS

Statistical analysis of engine parameters logs (included with EzTrends software: Flt#10 of duration 5.58 hours and Flt#11 of duration 3.69 hours, Continental TSIO-550?) was performed and Box-Wiskers plot was used for graphical representation of key values from summary statistics. Values represented in the summary are the mean, std. dev., minimum, maximum, 1th percentile and 99th percentile:

\[
[\mu_p, \sigma_p, \min(p), \max(p), p_{1\%}, p_{99\%}]
\]

The mean value for parameters \( p \) is determined by

\[
\mu_p = \frac{1}{N} \sum_{j=1}^{N} p_{ij}
\]

and the standard deviation is determined by

\[
\sigma_p = \sqrt{\frac{1}{N} \sum_{j=1}^{N} (p_{ij} - \mu_p)^2}
\]

where \( N \) is the number of records.

Percentile is the value of a variable below which a certain percent of observations fall. For example, the 99th percentile is the value below which 99% of the observations may be found. Percentiles are very suitable for exploring the distribution of number sets using various
Parameters present in a log of analyzed engine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGT 1-6</td>
<td>Exhaust Gas Temperature¹</td>
</tr>
<tr>
<td>CHT 1-6</td>
<td>Cylinder Head Temperature¹</td>
</tr>
<tr>
<td>OIL TEMP</td>
<td>Oil Temperature¹</td>
</tr>
<tr>
<td>TIT 1</td>
<td>Turbine Inlet Temperature¹</td>
</tr>
<tr>
<td>TIT 2</td>
<td>Turbine Inlet Temperature 2¹</td>
</tr>
<tr>
<td>CDT</td>
<td>Compressor Discharge Temperature</td>
</tr>
<tr>
<td>IAT</td>
<td>Intercooler 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 Power²</td>
</tr>
<tr>
<td>CLD</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>

¹ included in a statistical summary (gray), ² histogram of values determined

The concept of switching between multiple regimes is introduced to separate engine parameter statistics for each engine regime. One way to determine engine working regime would be from clustered RPM/MAP combinations, Fig. 6. However, in usual operations only small subset of these combinations is used, yet it may happen that for some reason pilot select unusual RPM/MAP combination lacking historical data in available engine logs (e.g. outside clustered areas). Because engine operation is of central consideration here, engine regimes are determined from calculated percent of the maximal horse power (% HP). This is simple and logical choice instead of using more complex multivariate clustering based techniques (e.g. using RPM, MAP, OAT and FF). % HP is already calculated by engine monitor from RPM, MAP, OAT and FF. Resulting percentage of Horse Power (% HP), is used as a proxy for determining engine regime. Fig. 7 illustrates calculated % HP as a function of RPM and MAP values. Histogram of statistical distribution for % HP is shown in Fig. 8. Same data presented in six bins corresponding to six engine regimes is shown in Fig. 9. Engine regime selection is shown in Table V and Fig. 10.

B. Multiple Engine Regimes

In ideal case one would determine distribution of engine parameters for each engine working regime corresponding to various flight phases: engine run up, take-off, climb and full throttle operation cruise and descent. Engine, propeller and mixture combinations for various flight phases are presented in Table IV, [3].
giving averaged power (climb, cruise) or engine run-up, monitor doesn’t provide different ranges depending on the current flight phase. Because the temperature values of value and abbreviation of the problematic parameter.

Default alarm limits are conservatively set (by JPI) below engine manufacturers (Lycoming and Continental) recommendations, Table VI. If a parameter gets out of its normal limits, the digital display will blink indicating the value for **DIF** is the difference between the hottest and coolest **EGTs**. This **EGT** span is important for monitoring the values of **EGTs**, [2]. Default alarm limits are set to encompass all flight regimes (“one fits all”). Engine monitor used in an experiment has default settings for limits shown in Table VI. Simple limit checking is used for exceedance warnings. Two limit values, thresholds, are present, a maximal value \( Y_{\text{max}} \) and a minimal value \( Y_{\text{min}} \). A normal state is when

\[ Y_{\text{min}} \leq Y(i) \leq Y_{\text{max}} \]  

To counteract effect of short application of power bursts by engine throttle that don’t have immediate effect on engine temperatures (that change more slowly), moving average of several samples (e.g. \( N=5 \)) may be applied to calculated \% **HP** values \( P_i \) as a form of low pass filter giving averaged power \( \hat{P} \) and consequently regime \( r \):

\[ \hat{P} = \frac{1}{N} \sum_{i=1}^{N} P_i \]  

\[ r = \left\lfloor \frac{\hat{P}}{20} \right\rfloor + 1 \]  

Statistical plots engine parameters for various engine regimes are shown in Fig. 11-16. Dependence of engine parameters on calculated \% **HP** \( (P_i) \) is clearly evident (please note different auto scales for temperature axis).

### VI. ALARM LIMITS

The EDM has several programmable owner-programmable exceedance settings for all parameters. Exceedance warnings are both visual and aural. When a parameter falls outside normal limits, the display flashes its value and acronym. Once the parameter value returns within its normal limits, the flashing stops.

#### A. Default Alarm Limits

Default alarm limits are conservatively set (by JPI) below engine manufacturers (Lycoming and Continental) recommendations, Table VI. If a parameter gets out of its normal limits, the digital display will blink indicating the value and abbreviation of the problematic parameter. Because the temperature values of **EGTs** can assume different ranges depending on the current flight phase (climb, cruise) or engine run-up, monitor doesn’t provide alarm limits for individual **EGTs**, it calculates the **DIF** parameter instead. The value for **DIF** is the difference between the hottest and coolest **EGTs**. This **EGT** span is important for monitoring the values of **EGTs**, [2].

### Table VI 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><strong>CHT</strong></td>
<td>450 °F 230 °C</td>
<td></td>
</tr>
<tr>
<td><strong>OIL</strong></td>
<td>90 °F 32 °C</td>
<td>230 °F 110 °C</td>
</tr>
<tr>
<td><strong>TIT</strong></td>
<td>1650 °F 900 °C</td>
<td></td>
</tr>
<tr>
<td><strong>CLD</strong></td>
<td>-60 °F/mm -33 °C/mm</td>
<td></td>
</tr>
<tr>
<td><strong>DFP</strong></td>
<td>500 °F 230 °C</td>
<td></td>
</tr>
<tr>
<td><strong>MAP</strong></td>
<td>32 inch Hg</td>
<td></td>
</tr>
</tbody>
</table>

Big advantage of limit checking is its simplicity and reliability, [4]. Maximal value \( Y_{\text{max}} \) and a minimal value \( Y_{\text{min}} \) are determined from parameter statistics

\[ L_{L_i} < p_i < L_{H_i} \]  

where

\[ L_{L_i} \] is low limit for parameter \( p_i \)

\[ L_{H_i} \] is high limit for parameter \( p_i \)

\( p_i \) is engine parameter \( i \)

Most parameters don’t need lower limit and only high limit is used (e.g. temperature too high). Oil temperature and fuel flow need both limits (low oil viscosity allow low temperature and abnormal fuel consumption). Alarm levels for warning alert (that require immediate crew awareness and corrective action) commonly set at the engine monitor are universal for all phases of flight and provide detection of serious faults.

#### B. Engine Regime Dependent Alarm Limits

Determination of the appropriate threshold could be quite difficult task [5, 6]. In this method it is supposed that record form the engine log should be closer examined if the value of engine parameter falls above value of 99% percentile or below value of 1% percentile if lower limit is used for that parameter (both rare events). This choice is experience based, considering the tradeoff in accuracy, [6]. Fine detection suitable for caution alert (corrective action may be required) is achieved by statistical analysis of engine parameters within each engine regime. Parameter range that is acceptable for one engine regime may be different for other regimes. Engine parameter statistics is collected and analyzed. Alarm limits are determined from extracted statistical data supplied in engine monitor logs. Limit values (1 and 99 percentiles) for parameters \( p_i \) and regime \( r \) are shown in Table VII. **OLT** and **FF** use both limits. Just upper limit is used for **EGT** and **TIT** and **CHT**.

\[ L_{L_{i,r}} < p_i < L_{H_{i,r}} \]  

\[ p_i < L_{H_{i,r}} \]

where \( L_{L_{i,r}} \) and \( L_{H_{i,r}} \) are low and high limits for regime \( r \).
Engine monitor is capable of displaying EGT-CHT patterns suitable for fault detection. Patterns consist of bar graphs, darker bars represent EGT and lighter bars CHT values. Each pattern corresponds to one or more engine problems. Proposed pattern recognition technique employed in this method is rule based. This is due to rather precise fault pattern descriptions available in pilot’s guide that comes with the engine monitor, [1]. There is also a lack of numerous real world patterns that would otherwise justify use of some statistical pattern recognition techniques. Rules are defined as descriptions in English language, usually one sentence and catalogued in manual. Following parameters (measured and calculated) are used in rules that describe conditions for fault pattern: $EGT_{max}$, $EGT_{min}$,$CHT_{max}$, $CHT_{min}$, $DIFF$ and $RPM$. Here is a list of catalogued patterns (six cylinder engine), but now with derived simple mathematical description (conditions) suitable for program implementation. Resulting conditions are described in relations (10) - (21).

1. $75^\circ$ to $100^\circ$ EGT rise for one cylinder during flight

   ![Pattern 1](image)

   **Figure 17. Pattern 1**

   CAUTION if $abs(EGT_{max} - EGT_i) > 75$ for any $i=1,\ldots,6$ (10)

2. EGT increase or decrease after ignition system maintenance
   - not implemented (external information about maintenance is needed)

3. Loss of EGT for one cylinder

   ![Pattern 3](image)

   **Figure 18. Pattern 3**

   CAUTION if $EGT_{min} < 600$ (11)

4. Loss of EGT for one cylinder; no digital EGT
   - not implemented, imprecise log entry definition

5. Decrease of EGT for one cylinder

   ![Pattern 5](image)

   **Figure 19. Pattern 5**

   CAUTION if $600 < EGT_{min} < 1000$ (12)

6. Decrease of EGT for one cylinder at low RPM

   ![Pattern 6](image)

   **Figure 20. Pattern 6**

   CAUTION if $DIFF > 500$ AND $RPM < 1500$ (13)

---

**TABLE VII** 1% and 99% percentile values for various engine parameters and engine regimes (used limits are shaded)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Regime 1</th>
<th>Regime 2</th>
<th>Regime 3</th>
<th>Regime 4</th>
<th>Regime 5</th>
<th>Regime 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$EGT_{min}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$EGT_{max}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$CHT_{min}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$CHT_{max}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$DIFF$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$RPM$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7. EGT and CHT not uniform (injection engines only)

WARNING if \((\text{EGT}/\text{CHT}) < 3\) OR \((\text{EGT}/\text{CHT}) > 6\) for any \(i = 1,\ldots,6\) \((14)\)

8. Decrease in EGT for all cylinders

WARNING if \(\text{EGT} < 1200\) for all \(i = 1,\ldots,6\) \((15)\)

9. Slow rise in EGT, low CHT

WARNING if \(\text{EGT} > 1600\) and \(\text{CHT} < 300\) for any \(i = 1,\ldots,6\) \((16)\)

10. High CHT on cylinders on one side of engine

WARNING if \(\text{abs} (\text{CHT}_{\text{left}} - \text{CHT}_{\text{right}}) > 100\) \(\text{left} = 2,4,6\) \(\text{right} = 1,3,5\) \((17)\)

11. Rapid rise in EGT/CHT of one cylinder

WARNING if \(\text{EGT} > 1650\) and \(\text{CHT} > 400\) for any \(i = 1,\ldots,6\) \((18)\)

12. Sudden off scale rise for any or all cylinders

WARNING if \(\text{EGT}_{\text{max}} > 1650\) for any \(i = 1,\ldots,6\) \((19)\)

13. Loss of peak EGT - not implemented, leaning process

14. Decrease in peak or flat EGT response to leaning process - not implemented, leaning process (mixt. adj.)

15. Bellow 10,000 ft full throttle causes EGTs to rise - not implemented, 10,000 ft info needed

16. CHT more than 500º, EGT normal. Adjacent EGT may be low

WARNING if \(\text{CHT}_{\text{max}} > 500\) AND \(\text{EGT}_{\text{max}} < 1600\) \((20)\)

17. Large DIFF at low RPM

WARNING if \(\text{DIFF} > 500\) AND \(\text{RPM} < 1500\) \((21)\)

All records in the engine log could be checked for fault patterns using procedure and derived conditions:

\[
\text{for record} = 1 \text{ to last} \\
\text{find } \text{EGT}_{\text{max}}, \text{EGT}_{\text{min}}, \text{CHT}_{\text{max}} \text{ and } \text{CHT}_{\text{min}}, \text{get DIFF and RPM} \\
\text{for } i = 1 \text{ to } N_{\text{patterns}} \text{ check conditions for pattern}(i) \\
\]

VIII. CONCLUSION

Proposed method combines default engine monitor limits, statistical analysis of engine parameters for different engine working regimes and rule based pattern recognition. Based on graphic presentation of available engine data percent of the maximal horse power (% HP) was chosen as a variable for regime selection. Engine parameter statistics were determined for all engine regimes and presented using exploratory data analysis Box-Wiskers plots. Method is primarily intended for parsing engine log after the flight. Build in default engine monitor alarm limits are preserved for the detection of severe engine problems and issuing warning alerts. Tighter limits are imposed on engine parameters for each particular engine regime and for detecting finer engine problems and issuing caution alerts. Upper limits are 99 percentile of engine parameters for a particular regime (for oil temperature and fuel flow additional 1 percentile is used for lower limits). Mathematical description for most fault patterns is produced from linguistic description and expert opinion. Such mathematical descriptions in terms of pattern conditions are suitable for rule-based pattern recognition. With larger scale statistics (including more flights) and determination of reliable thresholds (adding minimal parameter deviation periods) the method could be applied in real time with indications in a cockpit.

REFERENCES


