

# Engine Fault Detection in a Twin Piston Engine Aircraft

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**Abstract - Due to the inherent reliability of aircraft engines examples of engine faults are very rare. Hence, it is very difficult to devise mathematical models necessary for the fault detection. However, in case of twin engine aircrafts it is possible to detect potential engine faults by comparing parameters of both engines. In ideal case these parameters should be quite similar and their discrepancy could provide warning of the pending engine problem or failure. A method that uses statistically determined intervals is proposed.**

## I. INTRODUCTION

In most twin-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 failure is rare, thankfully, but does happen. Most engine damage which leads to failure does not occur all at once. If a pilot operates an engine in a way that causes excessive heat, stress or wear, it may take months before damage to the engine is severe enough to be detected by the pilot. By monitoring engine parameters it is possible to detect minor engine problems before they become large ones.

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 only detection of serious faults. Twin engine aircraft has two essentially the same engines. Fine detection is suitable for caution alert (where corrective action may be required) could be achieved by noticing the asymmetry of engine parameters. It is highly unlikely that both engines will fail in the same way at the same time with the same changes in corresponding engine parameters. Comparing engine parameters between the two engines enables fine detection of minor problems. Engine monitor log analysis can be performed after the flight using the proposed procedure and suspicious minor problems may be automatically labeled in the log for closer attention of the mechanic.

## II. AIRCRAFT PISTON ENGINE

Piston engine 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. In the past radial engines were also common. Engines have old fashion but reliable fixed-

timed dual magneto ignition systems (no use of electronics). Propellers are generally directly driven by an engine, although gearbox speed reducers exist on some higher power engines.

Engine problem, is likely to manifest itself as a partial engine failure in the first instance (e.g. cylinder failure). Total engine failure is more rare event and is defined as off the ground, total and mechanically caused (i.e. rod, crankshaft, stuck valve). Piston engine reliability data is shown in Table I. These numbers are obtained from pilot experiences participating in high traffic newsgroup *rec.aviation.ifr* with pilots reporting total hours flown and number of experienced partial and total engine failures, [1]. Piston engines are roughly seven times less reliable than jet engines. Engine monitoring can increase operational reliability of piston engines.

TABLE I. Reliability of typical piston engine (total failures)

Aircraft ownership	MTBF (hours)*
club	≈ 20.000 (18,390)
private	> 30.000 (30,775)

\*exact numbers derived from participant responses are in parentheses

The failure rate is not uniform, and depends a lot on how the aircraft are maintained and utilized (club vs. private airplane). Generally, better results are obtained for simpler engines like (IO-240, IO-320 and IO-360 then for more complex and powerful injection (IO-520, IO-540 and particularly turbocharged engines (TIO) where the turbo failure cause very significant power loss. In terms of engine reliability simpler designs give better results. Statistics is skewed toward four cylinder engines because they are most common among light airplanes.

## 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 than 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



Figure 1. Engine monitor display (EDM 760) for twin-engine aircraft

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 combustion process that generates power indicates engine problems like low compression, non-uniform fuel distribution, faulty ignition, and clogged injectors, [2].

Engine monitor used in an experiment records numerous engine parameters that are listed in Table II and shown in form of bar graph and digital display. Parameters are displayed and recorded at the programmed interval of between 2 and 500 seconds (in case of EDM 760 default setting is every 6 seconds). Voltage parameters are also recorded but they are not used for engine diagnostics.

TABLE II. Monitored engine parameters

Parameter	Description
EGT	Exhaust Gas Temperature
CHT	Cylinder Head temperature
OIL	Oil Temperature
TIT	Turbine Inlet Temperature
CLD	CHT Cooling Rate*
DIF	EGT Span**
FF	Fuel Flow***

\* fastest cooling cylinder, \*\* difference between the hottest and coolest EGT, \*\*\* with the fuel option installed

The used engine monitor (EDM 760) has several programmable alarms limits related to engine parameters. Default alarm limits are conservatively set (by JPI) below engine manufacturers (Lycoming and Continental) recommendations, Table III. 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 DFT 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"). If one would have information about the current flight regime these limits could be

TABLE III. Default Engine Monitor Alarm Limits

Measurement	Default Low Limit	Default High Limit
CHT		450 °F 230 °C
OIL	90 °F 32 °C	230 °F 110 °C
TIT		1650 °F 900 °C
CLD		-60 °F/min -33 °C/min
DIF		500 °F 280 °C

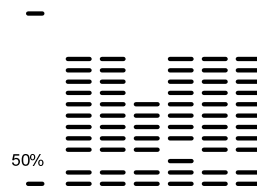


Figure 2. Intake valve or valve filter

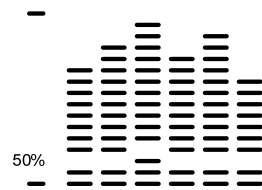


Figure 3. Dirty fuel injectors or fouled plugs

set to different levels for each flight regime. Automatic detection of the flight phase would require additional flight and engine parameters (altitude, speed, vertical speed and engine RPM with provisions for faulty sensor). However, these parameters are rarely readily available in digital format in general aviation aircraft (ageing fleet of average age 25+ years, still depending on analog gauges).

Engine diagnosis charts supplied with the engine monitor can help diagnose various engine faults, [2]. There are 15 general patterns that indicate particular faults, two examples are illustrated in Fig. 2 and Fig. 3.

#### IV. POSSIBLE APPROACHES

One possible approach for the early detection of engine problems would be to collect numerous engine monitor logs depicting various examples of engine failures. Combined with the large number of examples of normal engine it would be possible to train a pattern recognition system using collected labeled examples, [3, 4]. However in reality, because engine failures are quite rare, it would be very difficult (without organizing large scale voluntary action) to obtain a sufficiently large number of recorded engine failures (together with numerous examples of various faults to cover all important situations).

Another approach is to use some of novelty detection techniques, [5]. Novelty detection is a paradigm in which model of normality is constructed from normal system data. The primary objective of novelty detection is to examine if a system significantly deviates from the initial baseline condition of the system, Fig. 4. Novelty detection methods are particularly suited for applications where most data is available from normal system operation and failures are rare.

Most common novelty detection approaches are statistical and rule based approaches.

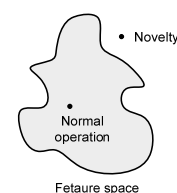


Figure 4. Novelty pattern in a feature space

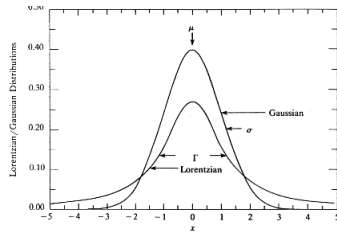


Figure 5. Gaussian distribution and deviations, Lorentzian for fat tails

In statistical approaches stochastic distribution is used to model the empirical data. Common assumption behind measured data is a Gaussian or normal distribution (mixture of normal distribution can also be used). If empirical distribution has very extended wings, Lorentzian may be appropriate. Pattern is considered a novelty when probability density function falls below a threshold (often associated with  $3\sigma$  distance from the mean  $\mu$  in case of normal distribution), Fig. 5. Determination of the appropriate threshold could be quite difficult task.

Rule based techniques automatically generate rules (or use rules devised by an expert) which capture the normal behavior of a system. Here are simple examples:

```
IF parameter < LIMIT1 THEN ALARM
IF parameter > LIMIT2 THEN ALARM
IF parameter < LIMIT1 OR parameter > LIMIT2 THEN ALARM
```

Engine monitor used in an experiment has default settings in form of following rules (limits from Table III):

```
IF CHT > 450 THEN ALARM
IF OIL < 90 OR OIL > 230 THEN ALARM
IF TIT > 1650 THEN ALARM
IF CLD < -60 THEN ALARM
IF DIFF > 500 THEN ALARM
```

## V. DESCRIPTION OF THE METHOD

### A. General Idea

Both engines on twin engine aircraft are the same with possible one small detail: on aircraft with counter-rotating propellers there are left and right turning engine, these engines are essentially the same with difference in cylinder firing order. Most (almost all) piston-engine airplanes offer a three-lever engine control setup that dates back more than 50 years. Two levers control the engine (power and mixture) whilst third lever controls propeller pitch (that has also great influence on engine RPM). In twin engine aircraft these levers are organized in a way that power, mixture and propeller pitch levers are positioned side by side as illustrated in Fig. 6. Generally, engine levers are always advanced in unison, the exceptions being during ground operations (startup,

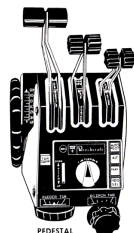


Figure 6. Engine control quadrant: power, propeller and mixture levers

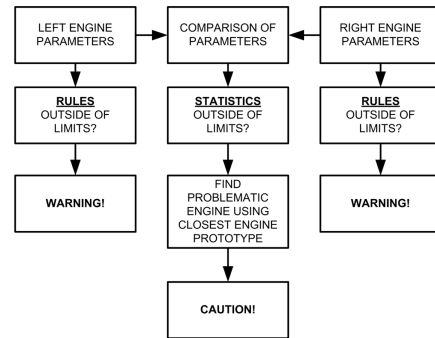


Figure 7. The general idea behind the method

shutdown, engine run-up with magneto checks), engine failure (simulated or real) and leaning procedure (adjust fuel/air ratio - mixture adjustment at altitude change).

Engine parameters are collected from engine monitor probes installed on an engine. It is expected that in normal operation parameters from left and right engine will be almost identical. By comparing parameters from the left and right engine small discrepancies could be detected. Default alarm levels (set by rules and limits, Table III) are still operative and ensure severe fault detection, while asymmetry of the engine parameters is used for finer detection of smaller problems, Fig. 7.

### B. Engine Parameters

Following parameters are collected or calculated by the engine monitor,  $N_C$  is the number of cylinders:

- Exhaust Gas Temperature for cylinders 1- $N_C$
- Cylinder Head Temperature for cylinders 1- $N_C$
- Oil temperature: OIL
- Turbine Inlet Temperature: TIT
- Fuel Flow: FF
- Cooling Rate: CLD

Other parameters (battery voltage, remaining fuel etc.) collected by the monitor are not used in this method.

There is a considerable spread of engine parameters during various phases of the flight, as shown (example of CHT values) in Fig. 8 that prevents use of tighter alarm levels (tightly set alarm level suitable for one flight phase would be busted in other flight phase). While the spread of individual engine parameters during the flight is quite large, spread of differences of parameters collected from two engines on a twin engine aircraft is significantly smaller, Fig. 8. When the difference between parameters  $\Delta p_i$  is small relatively to parameters better results could be achieved with relative difference  $\Delta_i p_i$  between parameters  $p_{i,L}$  and  $p_{i,R}$  from the left and right engine, Table IV:

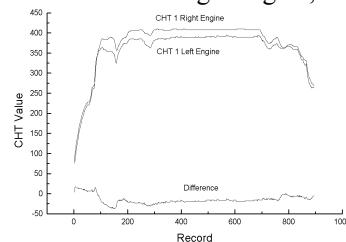


Figure 8. Example of CHT values for the same cylinder on the left and right engine and their difference

$$\Delta_r p_i = \frac{2(p_{i,L} - p_{i,R})}{abs(p_{i,L}) + abs(p_{i,R}) + \varepsilon} \quad (1)$$

Relative difference removes the influence of parameter magnitudes and the term  $\varepsilon$ ,  $\varepsilon \ll 1$ , prevents zero divisions.

TABLE IV. Parameters and their relative differences  $\Delta_r$

Parameter		Relative difference
Left Engine	Right Engine	
$EGT_{1-Nc,L}$	$EGT_{1-Nc,R}$	$\Delta_r EGT_{1-Nc}$
$CGT_{1-Nc,L}$	$CGT_{1-Nc,R}$	$\Delta_r CGT_{1-Nc}$
$OIL_L$	$OIL_R$	$\Delta_r OIL$
$TIT_L$	$TIT_R$	$\Delta_r TIT$
$FF_L$	$FF_R$	$\Delta_r FF$
$CLD_L$	$CLD_R$	not used for statistics, rules limits only

When considering parameters used in the method it is possible to distinguish two classes of parameters:

- Direct parameters – direct measurements, determined without considering values from other measurements

Direct parameters are snapshot of the moment and include following readily available engine parameters:

$EGT$ ,  $CHT$ ,  $OIL$ ,  $TIT$ ,  $FF$  (description in Table II)

- Derived parameters – determined from values of other measurements (differences or even time difference)

Derived parameters reflect the EGT parameter span or changes of parameters over the time (fastest cooling cylinder and rates of cylinder's temperature changes):

$DIF$  (EGT span),  $CLT$  (negative values shown only),  $\Delta CHT$

Beside available engine monitor parameters temperature differences  $\Delta CHT$  in one minute interval for cylinder heads are introduced in this method (one for each cylinder):

$$\Delta CHT_i = CHT_{i,k} - CHT_{i,k-20} \text{ one minute span (6s record)} \quad (2)$$

Simple difference between left and right engine is used:

$$\Delta(\Delta CHT_i) = \Delta CHT_{i,L} - \Delta CHT_{i,R} \text{ (due to small differences)}$$

Parameters  $CLT$  and  $\Delta CHT$  reflect temperature changes of an engine. All parameters are organized in two vectors, for the left engine  $\mathbf{v}_L$ , ( $N_C$  is the number of cylinders):

$$\mathbf{v}_L = [EGT_1, \dots, EGT_{N_C}, CHT_1, \dots, CHT_{N_C}, \Delta EGT_1, \dots, \Delta EGT_{N_C}, OIL, TIT, FF] \quad (3)$$

and for the right engine  $\mathbf{v}_R$ :

$$\mathbf{v}_R = [EGT_1, \dots, EGT_{N_C}, CHT_1, \dots, CHT_{N_C}, \Delta EGT_1, \dots, \Delta EGT_{N_C}, OIL, TIT, FF] \quad (4)$$

### C. Decision Criterion

The decision is based on thresholds imposed on relative differences (simple difference for  $\Delta(\Delta CHT_i)$ ):

$$T_{EGT,LOW} < \Delta_r EGT_i < T_{EGT,HIGH} \quad i=1, \dots, N_C \quad (5)$$

$$T_{CHT,LOW} < \Delta_r CHT_i < T_{CHT,HIGH} \quad i=1, \dots, N_C \quad (6)$$

$$T_{\Delta CHT,LOW} < \Delta(\Delta CHT_i) < T_{\Delta CHT,HIGH} \quad i=1, \dots, N_C \quad (7)$$

$$T_{OIL,LOW} < \Delta_r OIL < T_{OIL,HIGH} \quad (8)$$

$$T_{TIT,LOW} < \Delta_r TIT < T_{TIT,HIGH} \quad (9)$$

$$T_{FF,LOW} < \Delta_r FF < T_{FF,HIGH} \quad (10)$$

A suspicious condition is detected when at least one of inequalities is not fulfilled. If asymmetry of parameters is detected than one should be suspicious about condition of

one of engines. However there is still no information which engine is causing the problem, as both engines may still be well within default alarm limits. In that case engine parameters are normalized and compared with normalized prototype patterns from a pool stored for each engine and chosen using nearest neighbor rule.

The prototype pattern is a vector  $\mathbf{v}_P$  that consists only of following  $2N_C$  components:

$$\mathbf{v}_P = [EGT_1, \dots, EGT_{N_C}, CHT_1, \dots, CHT_{N_C}] \quad (11)$$

### D. Pattern Normalization

Normalization is performed by determining the highest  $EGT$  among all cylinders of an engine. Then all  $EGT$  and  $CGT$  values are divided by the previously determined highest  $EGT$  value.

$$EGT_{MAX} = \max(EGT_i) \quad i=1, \dots, N_C \quad (12)$$

Normalized  $EGT$  values,  $NEGT$  are:

$$NEGT_i = \frac{EGT_i}{EGT_{MAX}} \quad i=1, \dots, N_C \quad (13)$$

Similarly, normalized  $CHT$  values,  $NCHT$  are:

$$NCHT_i = \frac{CHT_i}{EGT_{MAX}} \quad i=1, \dots, N_C \quad (14)$$

Components of the normalized pattern are within intervals:

$$0 \leq NEGT_i < 1 \quad i=1, \dots, N_C \quad (15)$$

$$0 \leq NCHT_i < 1 \quad i=1, \dots, N_C \quad (16)$$

The normalized prototype pattern now has following  $2N_C$  components:

$$\mathbf{v} = [NEGT_1, \dots, NEGT_{N_C}, NCHT_1, \dots, NCHT_{N_C}] \quad (17)$$

### E. Normalized Prototype Patterns

Four normalized prototype patterns are determined both for the left and right engine using previously available engine data. They are determined by analysis of engine operation log at points where average  $CHT$  for all cylinders crosses for the first time temperature levels 200, 250, 300 and 350 °F, Table V (to avoid unsupervised clustering procedure). Various engine operation regimes are covered, i.e. engine is not represented by single normalized prototype pattern for all the duration of flight. Patterns are normalized to minimize influence of different parameter magnitudes from various flight phases, Fig. 8.

TABLE V. CHT temperatures for prototype patterns

Pattern	CHT transition temperature* (°F)
1	↑ 200
2	↑ 250
3	↑ 300
4	↑ 350

\* temperature up-transitions

### F. Detection of Suspicious Engine

Normalized pattern from each engine is compared with closest normalized patterns from a pool of stored patterns using the Euclidean distance measure. Closest normalized prototype is chosen for each engine considering  $CHT$  of individual cylinders and  $CHT$

transition temperature from Table V using  $k$ -nearest neighbor algorithm. The  $k$ -nearest neighbor algorithm assigns the object to the class most common amongst its  $k$  nearest neighbors, [4]. In case of six cylinder engine 6-NN rule is applied. Closest pattern is the one whose CHT transition temperature is closest to CHT values of most cylinders. This procedure selects the correct normalized prototype pattern even when one or more CHT values are outliers (e.g. due to a cylinder failure). Once the closest normalized prototype pattern is chosen, Euclidian distances between vectors of engine parameters represented in normalized engine pattern and selected normalized prototype patterns are determined for both engines. In general, for an  $n$ -dimensional space, the Euclidean distance is given by

$$d(p, q) = \sqrt{(p_1 - q_1)^2 + (p_2 - q_2)^2 + \dots + (p_n - q_n)^2} \quad (18)$$

$$dist_{E,P} = \sqrt{\sum_{i=1}^{i=N_C} (NEGT_{E,i} - NEGT_{P,i})^2 + \sum_{i=1}^{i=N_C} (NCGT_{E,i} - NCGT_{P,i})^2} \quad (19)$$

Average values (and hence appropriate differences) are larger for  $NEGT$  than for  $NCGT$ . Equalization term is introduced based on average ratio  $NEGT$  and  $NCGT$  (across all cylinders  $i$  and all records  $k$ ) from engine logs:

$$R = \frac{1}{N_C N_R} \sum_{i=1}^{N_C} \sum_{k=1}^{N_R} \frac{NEGT_{i,k}}{NCGT_{i,k}} \quad (20)$$

Value for  $R$  is approximately set to value 4.2 (not to complicate (19) with introduction of the variance for each parameter).  $N_R$  is the number of records, and  $N_C$  cylinders

$$dist_{E,P} = \sqrt{\frac{1}{R^2} \sum_{i=1}^{i=N_C} (NEGT_{E,i} - NEGT_{P,i})^2 + \sum_{i=1}^{i=N_C} (NCGT_{E,i} - NCGT_{P,i})^2} \quad (21)$$

Appropriate distances for left and right engine are given by:

$$dist_{E,L_i} = ED(v_E, v_{P_{L_i}}) \quad i=1, \dots, 4 \quad (22)$$

$$dist_{E,R_i} = ED(v_E, v_{P_{R_i}}) \quad i=1, \dots, 4 \quad (23)$$

Engine whose normalized engine pattern  $v_P$  is further distance to selected normalized prototype pattern is indicated (or labeled) to be suspicious.

### G. Determination of Thresholds

Thresholds are determined from extracted statistical data supplied in engine monitor logs. Decision for this time period was made considering MTBF values of piston engines and maintenance intervals (50, 100 and 200 hours for engines). In a real life we are generally not satisfied with the notification of the failure, but the notification of the impending failure, so maintenance and service actions can be taken in advance, before the failure happens. It is decided that for each parameter there should be one caution alert within 100 hour period,  $T_{ALERT}$ , much lower than estimated MTBF. It seems reasonable to label suspicious parameter spread in an engine monitor log that will appear for particular parameter once in  $T_{ALERT}$  period and be brought to the attention of the mechanic. This is a balance between detection sensitivity and not generating too much burden for a mechanic. Frequency histograms

of parameter differences (levers advanced in unison) are shown in Fig. 9-14 (one example shown for  $\Delta_r EGT$  and  $\Delta_r CHT$ ). Normal distribution is assumed for all differences. For each difference mean value and standard deviation from engine monitor log is calculated across all records:

The mean value for parameters  $p_i$  is determined by

$$\mu_{p_i} = \frac{1}{N_R} \sum_{j=1}^{N_R} p_{i,j} \quad (24)$$

and the standard deviation is determined by

$$\sigma_{p_i} = \sqrt{\frac{1}{N_R} \sum_{j=1}^{N_R} (p_{i,j} - \mu_{p_i})^2} \quad (25)$$

where  $N_R$  is the number of records)

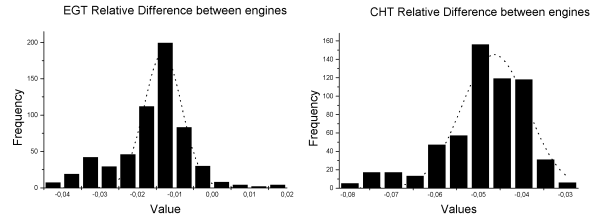


Figure 9.  $\Delta_r EGT$  example

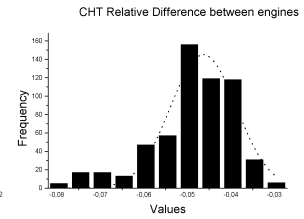


Figure 10.  $\Delta_r CHT$  example

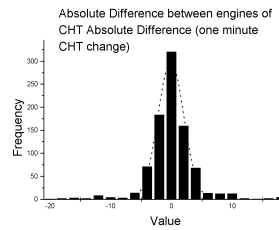


Figure 11.  $\Delta ACHT$

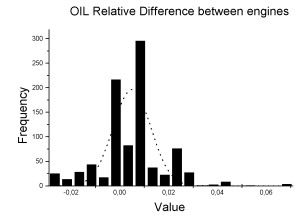


Figure 12.  $\Delta_r OIL$

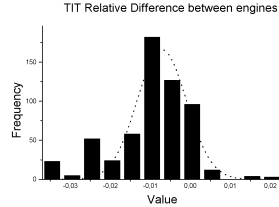


Figure 13.  $\Delta_r TIT$  - Turbine Inlet

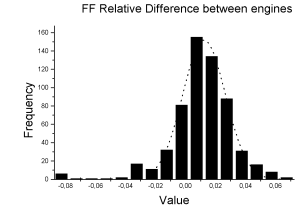


Figure 14.  $\Delta_r FF$  Fuel Flow

Due to the lack of available examples of engine failures, determination of acceptable deviations from the mean (for determination of lower and upper limit) is accomplished by the determination of the standard deviation  $\sigma$  of the normally distributed values in frequency beans, and using multiple of  $\sigma$ , [6]. Acceptable deviations from the mean values are determined based on the reasoning that an unacceptable parameter value happens at average once during the  $T_{ALERT}$  period. The  $N_R$  is number of records within  $T_{ALERT}$  period (100 hours) is given by

$$N_R = \frac{T_{ALERT}}{T_R} \quad (26)$$

$T_R$  is duration of one engine log record (default value 6s) As there will be at average one such "alert record" for each parameter within 100 hours probability  $p$  is 0,999983:

$$p = \frac{1}{N_R} \quad (27)$$

Proportion  $r$  of data values within  $z$  standard deviations of the mean is defined by:

$$r = erf\left(\frac{z}{\sqrt{2}}\right) \quad (28)$$

where

$$r = 1 - p \quad (29)$$

and  $erf$  is the error function

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \quad (30)$$

When observations under considerations are distributed according to the Gaussian distribution, 68% of observations fall within  $\sigma$ , 95% within  $2\sigma$  and 97% within  $3\sigma$  of mean. From the available  $T_{ALERT}$  and the duration of the engine log record  $T_R$  the probability,  $p$ , is determined, followed by  $r$ , and finally  $z$ . For given  $p=0,999983$ , value for  $z$  is 4.3006. Referent mean values  $\mu_{p_i,G}$  and standard deviations  $\sigma_{p_i,G}$  are determined from the previous engine monitor logs of a good engine. Log analysis is performed after flight. We are looking for a record that appears at average once during  $T_{ALERT}$  period. All parameters values  $p_i$  from each record of a good engine (i.e.  $p_{i,TG}$ ) will fall within predefined interval around mean,  $\mu_{p_i,G}$  (i.e. within the acceptance interval defined by the lower and upper thresholds,  $T_{LOW}$  and  $T_{HIGH}$ ):

$$T_{LOW} = \mu_{p_i,G} - z\sigma_{p_i,G} \quad (31)$$

$$T_{HIGH} = \mu_{p_i,G} + z\sigma_{p_i,G} \quad (32)$$

$$P_{i,TG} \in [\mu_{p_i,G} - z\sigma_{p_i,G}, \mu_{p_i,G} + z\sigma_{p_i,G}] \quad (33)$$

where  $\mu_{p_i,G}$  is the mean of the parameter  $p_i$  from a good engine,  $\sigma_{p_i,G}$  standard deviation of a parameter value  $p_i$  from a good engine,  $i = 1, \dots, N_P$ ,  $N_P$  is the number of parameters. On the other hand for one or more parameters values  $p_i$  of the problematic or failed engine (i.e.  $p_{i,TF}$ ) following relation will apply:

$$P_{i,TF} \notin [\mu_{p_i,G} - z\sigma_{p_i,G}, \mu_{p_i,G} + z\sigma_{p_i,G}] \quad (34)$$

Relations (33) and (34) use (5)-(10) in a different notation.

## VI. RESULTS

Several engine monitor logs were available from previous flights supplied with the EZTrends software, [7]. Analyzing log data from longest available flight (Flight sample #192, 1,46h) parameter differences have been determined. The first part of the log (engine start-up, magneto check and run-up) and the last part (shut down) were omitted as these are obvious situations of asymmetric engine operation. Mean values, standard deviations and thresholds are shown in Table VI. Relative parameter differences are within few percents.

## VII. CONCLUSION

It is expected that in normal operation both engine parameters will be almost the same. Comparing engine parameters between two engines may enable fine detection of minor problems. Proposed method combines rules (limits on the engine monitor parameters of the individual engine) and statistical approach (using relative differences with the exception of  $\Delta ACHT$ ). Threshold limits for comparison of parameters are calculated using statistical data from engine monitor logs considering the  $T_{ALERT}$  period (using engine maintenance interval). After

TABLE VI. Mean, Std. Dev. and Thresholds ( $z=4.3006$ )

Parameter difference ( $p_i$ )	Mean $\mu_{p_i,G}$	Std. Dev. $\sigma_{p_i,G}$	Lower Threshold $\mu_{p_i,G} - z\sigma_{p_i,G}$	Upper Threshold $\mu_{p_i,G} + z\sigma_{p_i,G}$
$\Delta_r EGT_1$	-0,01547	0,00987	-0,05792	0,02698
$\Delta_r EGT_2$	0,02211	0,00953	-0,01887	0,06309
$\Delta_r EGT_3$	0,01086	0,00899	-0,02780	0,04952
$\Delta_r EGT_4$	0,01796	0,00864	-0,01920	0,05512
$\Delta_r EGT_5$	-0,00445	0,00926	-0,04427	0,03537
$\Delta_r EGT_6$	0,00321	0,00904	-0,03567	0,04209
$\Delta_r CHT_1$	-0,0483	0,00967	-0,08989	-0,00671
$\Delta_r CHT_2$	0,02811	0,00703	-0,00212	0,05834
$\Delta_r CHT_3$	0,03352	0,00924	-0,00622	0,07326
$\Delta_r CHT_4$	0,04517	0,0131	-0,01117	0,10151
$\Delta_r CHT_5$	-0,03087	0,00866	-0,06811	0,00637
$\Delta_r CHT_6$	0,09124	0,01187	0,04019	0,14229
$\Delta ACHT_1^*$	-0,22912	3,87961	-16,91377	16,45553
$\Delta ACHT_2^*$	-0,05643	2,67721	-11,57004	11,45718
$\Delta ACHT_3^*$	-0,23251	3,6691	-16,01184	15,54682
$\Delta ACHT_4^*$	0,10609	2,24289	-9,53968	9,75186
$\Delta ACHT_5^*$	-0,47291	3,93404	-17,39164	16,44582
$\Delta ACHT_6^*$	-0,04853	2,9464	-12,71982	12,62276
$\Delta_r OIL$	0,00621	0,01279	-0,04879	0,06121
$\Delta_r TIT$	-0,00969	0,00913	-0,04895	0,02957
$\Delta_r FF$	0,01015	0,02051	-0,07806	0,09836

\*for  $\Delta ACHT_i$  simple differences are used instead of relative differences

detecting asymmetry of parameters, suspicious engine is detected by comparing the engine parameters with parameters of stored prototype patterns. Default alarm limits for individual engines (simple rules) are preserved for the detection of severe engine problems. Procedure is performed off-line as part of the analysis of recorded data after the flight. The engine log file is parsed and records with discrepancy of parameters between engines are automatically labeled as suspicious and can be brought to attention of maintenance personnel. This enables faster and more precise scan of the engine monitor log than simple visual inspection of engine parameter curves. With additional field tests and determination of reliable thresholds (including an additional time threshold defining the minimal parameter deviation period for issuing the caution alert) it would be possible to consider the real time version of the method implemented in some kind of the engine monitor with indication of the engine parameters asymmetry in a cockpit.

## REFERENCES

- [1] W. Emerick, "Engine failure stats" USENET: rec.aviation.ifr, Jan. 5., 2001 [24 Mar. 2012]
- [2] *Pilot's Guide EDM-760 Twin*, JPI, California, USA, 2005, Available: [http://www.jpitech.com/manuals/02/PG\\_EDM760.pdf](http://www.jpitech.com/manuals/02/PG_EDM760.pdf), [18 March 2012]
- [3] D. Miljković, "Fault Detection Methods: A Literature Survey", *Proc. MIPRO 2011, Vol. III, CTS & CIS*, pp. 110-115, Opatija 23-27 May 2011
- [4] R. Schalkoff, *Pattern Recognition: Statistical, Structural and Neural Approaches*, John Wiley, USA, 1992
- [5] D. Miljković, "Review of Novelty Detection Methods", *Proc. MIPRO 2010 - Vol. III: CTS & CIS*, pp. 27-32, MIPRO, Opatija 24-28 May 2010
- [6] D. Miljković, "Fault Detection for Aircraft Piston Engine by Exhaust Noise Analysis", *Proc. MIPRO 2011, Vol. III, CTS & CIS*, pp. 116-121, Opatija 23-27 May 2011
- [7] *EZTrends* (Download and Plotting Software), JPI, California, USA, Available: <http://www.jpitech.com/softwaredownload.php> [18 March 2012]