METHODOLOGY TO EVALUATE AIRCRAFT PISTON ENGINE DURABILITY

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ABSTRACT

A main problem in aircraft engines is the evaluation of residual life to TBO. The algorithm described in this paper calculates with good reliability the residual life to TBO of a petrol piston engine. The method was tested on small last-generation naturally-aspirated-avio piston engine, and has demonstrated to be effective in several experimental tests. This method is implemented directly in the FADEC or ECU of the engine with very few lines of C-Code. The method can be used also in many industrial engines.

This innovative method assumes that only two main factors (load and wear) affect engine durability or Time Between Overhauls (TBO). These two factors are considered as separate and combined with the worst case criteria. The load is assumed to follow a logarithmic law and a formula similar to the Miner’s law for material fatigue is used, making possible to calculate the “load curve” with the knowledge of only two points. The “wear” curve is related to elapsed engine cycles, and is easy to implement since it is related to technological. The resulting algorithm is very simple and can be implemented in very few software lines with data collected from the already existing sensors.

1. INTRODUCTION

The maintenance schedule is influenced by the “weariness” parameter, the aircraft engines are maintained on time basis not only of flight but also of engine run. Historically TBO (Time Between Overhaul) has been expressed in “hours”. The term “hours” has always been different from case to case. In some cases it meant the total number of revolutions of the crankshaft. This number can be measured with a mechanical or electronic device installed on the crankshaft. In other cases, for example in some light aircrafts, it meant simply the total time the engine has been running. In the automotive field the parameter is the road length (km) covered by the vehicle. Another parameter is the lubricant consumption rate. When this rate overcomes the limit given by the manufacturer, the engine should be overhauled. In the old Tempest WWII fighter with its huge Sabre engine, the TBO time was defined by the time when oil tank autonomy was inferior than fuel tank autonomy. In other words TBO was given by the time when the aircraft ended the lubricant before ending the high octane gasoline. The “weariness” parameter can be complicated at pleasure, for some vehicles the TBO depended on whether the vehicle was used in cities or in open roads. In F1 racing cars the engine durability is also affected by the number of times a certain engine speed has been overcome. This later indication was clearly linked by the fact that engine TBO depends on load and piston speed. In some modern automotive engine some sensors indicate when the oil is deteriorated and should be changed, but this criteria does not supersede the usual km-based criteria. The availability of the FADEC with its “small computer” makes it possible to improve the TBO criteria with a more sophisticated algorithm. However since TBO is strictly related to the engine reliability and the aircraft safety this algorithm should be kept as simple as possible. In fact software complication deteriorates reliability in an unpredictable way. This paper introduces an algorithm derived from racing experience. This algorithm is very simple and can be implemented in the FADEC with very few lines of code. This should reduce the debugging problem. The result is an on-line indication of the residual engine life for proper TBO scheduling. This paper is organized in two main parts, in the first part engine durability and maintenance criteria are discussed, while in the second part the algorithm is introduced.

2. ENGINE DURABILITY AND MAINTENANCE

2.1 Some considerations about current level of commercial technology for maintenance and wear prevention

Some years ago the main durability limit was on valves seats and valve train wear. Now the huge research work on this part of the engine has brought the limit to the wear of valve guides and piston rings. In some cases bearings and springs are subjected to failure, but this is usually linked to excessive engine performance expectations. Two main aspects should also be considered: on one side the choice of materials treatments and design-strategy for wear prevention, on the other side the approach to maintenance. In any practical application preventive maintenance should be applied to avoid risks of engine damage beyond economical recovery. The maintenance strategy is particularly critical. At the end of WWII, the ideal aircraft piston engine was the "maintenance free" power unit. The only maintenance required was fluids and filters substitution on time, hours or distance basis. The engine is sealed and will be opened only at TBO or in case of failure to pass the routine standard controls. In this case the very limited “maintenance” can be performed on field by personnel with “limited proper training”. Logistic is reduced to a minimum. This maintenance can be performed by virtually unskilled operators. Very limited equipment is required. After the life (indicated by the manufacturer) is expired or at the minimum suspect of “unsafe”, the engine is substituted with a new "zero hours" unit. This approach has been retained in some fields, for example in some industrial applications, in the transportation field(*), in the automotive field (*) and in some military (russian) aircrafts and helicopters. In the commercial aircraft field, dominated by turbines, highly trained operators perform scheduled inspections and substitute the worn out components. This approach makes it possible to prolong substantially the TBO. This approach is proved to be more economical than the “closed engine” approach especially for commercial airliners that have an organized and well structured maintenance system. In fact these very large engines are extremely expensive to replace and to overhaul.

Doubts arise on this approach for small organization and for military use. In any case it should be considered that durability is a critical choice that should be planned and defined in the requirements before starting the true design phase. Careful balance should be calculated between maintenance and overhaul costs to assess the total cost for engine “hour”.

In this optic a very important aspect is the design criteria, the appropriate choices of materials and treatments/coatings. Another very important aspect is the “environment”, not only in terms of temperature, humidity level… but also of operating conditions. For example ultralight aircraft are often subjected to “bizarre” maintenance or no maintenance at all.

The rod length, the squared average piston speed, true thermal loading and several other design factor have a well defined influence on engine durability.

Several research activities have taken place on the surface treatments in order to reduce friction, wear and to eliminate lubrication. Luckily the new rules in motor racing oblige the manufacturer to use the engine for a relative long mileage. This necessity have greatly improved the knowledge on the design criteria for long lasting piston engines. Plenty of data become to be available from test bench and from direct racing experience. Far less data are available on low or null load endurance. These tests are very time consuming and are very seldom performed. Luckily, a lot of data that correlate the engine life in terms of load, rpm and temperature are available. All this data can be used to foreseen engine TBO.

2.2 A simplified approach to very low load durability

As previously indicated very few data are available on low load or even engine durability at idle.

“Idle” is particularly critical since engine cooling may prove to be insufficient especially for gasoline engines in hot climate. Thermal overload is behind the corners in this case. This type of overload is particularly critical with aluminium alloys where a critical temperature is present. The overcome of this temperature puts the engine immediately out of service. Other issues regard oil flow and temperature with similar result in case of “not conservative” worst-case design.

All these cases are not considered in this paper, where the engine is supposed to be correctly designed, tested and installed. In any case a properly situated temperature control system can easily detect the thermal overloading and advise the user to take appropriate action. Overstress or overheating can be recorded in the FADEC and signalled to the maintenance crew for proper corrective action.

The method described in this paper will introduce an algorithm for the calculation of the residual life. This algorithm can be easily introduced in the software of the FADEC in very few lines of software code. This is based on the fact that ‘quality and reliability assurance of complex equipment and systems requires that all engineers involved in a project undertake a set of specific activities from the definition of the operating phase, which are performed concurrently to achieve the best performance, quality and reliability for given cost and time schedule targets’ [1].

3. BASIC IDEA AND INFLUENCE OF SEVERAL FACTORS

3.1 Basic hypothesis

The engine is well tested and it is ready for costumer use. It wears out in a known and controlled way. A well developed engine is subjected to progressive wear with an increase of blow-by that provokes a progressive increase in lubricant consumption rate. Another basic hypothesis is that the technologies used in the engines are well known and data about long endurance, “low or null load” condition are available.

An important condition is overloading. No thermal overload or over speed should take place.

In case of the above overloads the maintenance schedule should be modified accordingly.

Other basic assumptions are: the prescribed preventive maintenance is fully applied. A programmable FADEC is included in the engine and real-time engine running data are available. At a particular load level, rpm and a reference temperature are available.

The other component that are subject to wear are substituted at scheduled maintenance steps. By the way this schedule can be based on the residual life calculated by this algorithm.

3.2 The full load log curve

The basic idea of this method is to use a rule similar to the one of Palmgren-Miner’s for the fatigue of structural materials Eq. (1):

$$\sum_{i=1}^{n_{tt}} \frac{n_i}{N_i} = 1 \qquad (1)$$

Two basic curves are used: the full load curve and the number of cycles curve.
The first curve describes the endurance of the engine given a certain load.
This curve is based on the principle that wear linked to power follows a linear curve in the log diagram. As an example the load curve of a spark ignition aeronautical piston engine is depicted in figure 1.

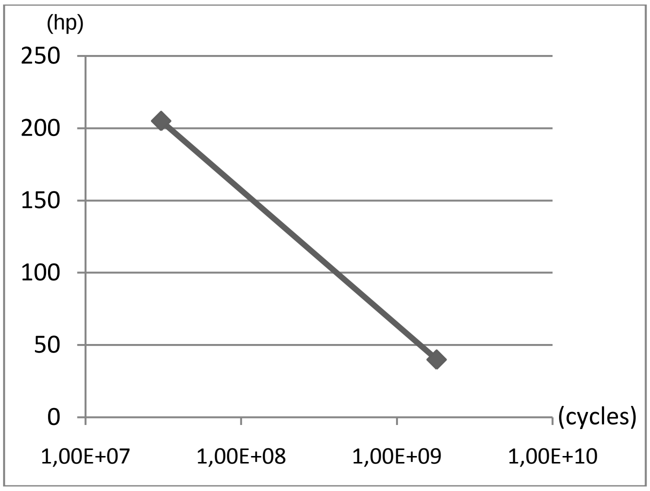


Figure 1: the load curve of an aeronautical spark ignition piston engine

After a certain number of cycles are elapsed, the FADEC calculates the average load (HP) and evaluates the life reduction. At the beginning the life is 1 (100%). For example, if 160 cycles are run at full load the used life is

$$n_{uaws} = \frac{n_i}{N_i} = \frac{160}{30600000} = 0.005 \qquad (2)$$

The residual life then is

$$n_{residual} = 1 - 0.005 = 0.995 \qquad (3)$$

Equation (1) is then modified as follows

$$\sum_{i=1}^{n_{tt}} \frac{n_i}{N_i} = 99.5\% \qquad (4)$$

On the display in the cockpit the residual life is 99.5%.
The curve was derived from full load endurance tests. These tests are usually performed at the maximum possible power for the engine at a specified crankshaft speed. This load level is usually higher than the service load level. In our case it is 120% the maximum allowed power (load) level.
This approach makes it possible to shorten the bench tests and to reduce costs. Unfortunately the full load data is strictly necessary.
The diagram of figure 1 terminates at 40 HP. In this lucky case the endurance at this power level is known. The diagram can be easily extrapolated to null or idle load level. On spark ignition engines the throttle is fully opened and the power level is given by the rpm level. These two points (full load and nearly null load) are then summarised in the HP-log(cycles) diagram of figure 1. However the engine is rarely running at full throttle (full load). For this reason an additional curve is necessary.

3.3 The low (null) load endurance

This data is rarely available. From our own experience, based on very high mileage automotive engine, the following assumption can be made:
A 4T traditional engine with less than 10,000 thermal cycles in the whole life lasts about 1,500 million of revolutions. For standard engine it is assumed an engine build with a cast iron block, standard segments, aluminium piston, appropriate lubrication, l/s>1.5 and $cm^2_{max} < 200$.
This figure is nearly doubled with cylinder liners coated with nikasil or similar coatings. However in our evaluation we use normally a 1.5 increase instead of 2 to take into account of deformations in light alloy engine blocks.
It is possible to increase this factor in a very significant way by using more durable surface treatments. An example of these treatments is reported in the paper "The influence of Honingy on the Wear of Ceramic Coated Piston Rings and Cylinder Liners", written by Radil, K, NASA/TM-2000-209794 [2].
The key parameter in this case the total wear volume loss. This parameter is afflicted by many factors, the more important is the average mean piston speed.

3.4 The wear related endurance curve

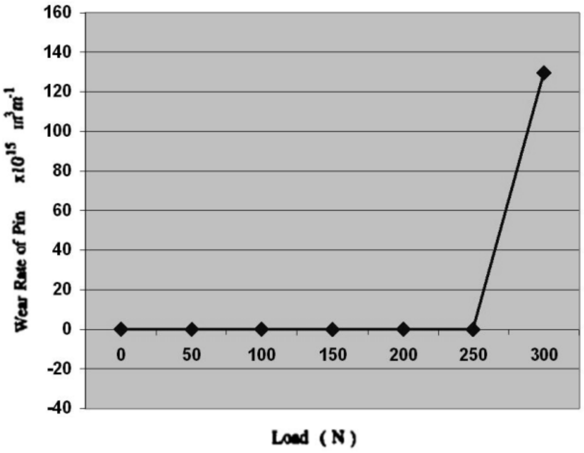
An rpm related curve is then introduced, this curve starts from the number of cycles at zero load and uses the principles that wears is related to distance covered by the piston. In fact, according to Archard expression, the wear coefficient k relates the volumetric wear rate with the applied load and the sliding distance, given by Eq. (5):

$$Q = kW\,DS \qquad (5)$$

The assumption that W is independent by piston speed is based on the fact that k depends more on material and lubrication than on the load W. Lubrication, with up-to-date lubricants and oil cooled pistons, is very good even at low rpm.
This fact is clearly shown in the diagram of figure 2 about the relation between load and wear rate of a pin (Jisheng and Gawne, 1996) [3]:

Figure 2. Wear rates of a steel with respect to load under a sliding speed of 2 m s -1 and lubricated conditions.

In the paper titled "Influence of lubrication regime on the sliding wear behaviour of an alloy steel" written by Jisheng and Gawne in 1996 [3], a constant wear was measured in the load range of 0-280 N.
Since wear is approximately independent from load, it is sufficient to calculate the total number of cycles that can be run by the engine. This is the old "hours" or "cycles" or "crankshaft revolutions" criteria [4].
Once the FADEC has calculated the factor reduction due to the load level, the residual life can be calculated on a number of cycle basis.
For example if our engine can run 1,500,000 revolutions and our engine has run for 254,000 revolutions, the residual life is:



$$residualLifeWear = \frac{(1{,}500{,}000 - 254{,}000)}{1{,}500{,}000} \approx 83\% \qquad (6)$$

The FADEC can then compare the residual life and the curve of figure 1. The worst of the two condition is used to evaluate the residual engine life.

3.5 The thermal cycling curve [5], [6], [7]

Another important factor in engine wear and endurance is the thermal cycling. As the engine is started it becomes to warm up to the operative temperature range. When the engine is stopped it cools down. As the engine regains room temperature a single thermal cycle is completed [8].
The number of thermal cycles is relevant to engine life. For example the engine of an aerobatic aircraft (that may fly thermal cycles of 8' each.) will last significantly less than an aircraft that makes longer flights.
In this case the parameter is the maximum allowed number of thermal cycles.
If hour engine has totalled 331 load cycles with a maximum allowed of 1000 cycles the residual life will be:

$$residualLifeThCycling = \frac{(1{,}000 - 331)}{1{,}000} \approx 67\% \qquad (7)$$

Again the residual life of Eq. (6) should be compared with the ones of Eq. (5) and Eq. (4).

4. CONCLUSIONS

It is possible to define an algorithm which is able to optimize maintenance and reliability of a piston engine, evaluating the residual engine life. It is possible through the comparison between two curves: the load curve and the rpm curve. In fact, the engine life is conditioned both by the load and by the number of cycles, which must be considered during the evaluation of the physical life [9].
The additional factor of thermal cycles has also be included.
This method proved to be effective in an naturally aspirated aircraft engine and it may be generalized as an industrial method for a better evaluation of TBO.

8. REFERENCES

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5. SYMBOL TABLE

n_i	number of cycles at a given load
Ni	maximum number of cycles at a given load
n_T	total number of load steps in the duty cycle
cm	average piston speed [m/s]
l	rod length[mm]
s	stroke [mm]
ω_{ll}	angular velocity for known # of cycles at low load [rad/s]
ω_{idle}	angular velocity at idle [rad/s]
Q	volumetric wear [mm^3] of the lower hardness body
k	wear coefficient [mm^3/(m.N)]
W	normal load [N]
DS	sliding run distance [m]

(*) In this field the approach is even more radical: the car with the worn out engine is disposed as a whole.