

Method for Evaluating the Durability of Aircraft Piston Engines

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Abstract

A significant issue in aircraft engines is quantifying residual life to overhaul. The algorithm described in this paper calculates with a good level of reliability the residual life of a petrol piston engine. The method was tested on small, latest-generation, naturally-aspirated aircraft and racing piston engines, and has been effective in several experiments. This method is implemented directly on the electronic control system of the engine with very few lines of C-code. The method can also be used in many industrial engines. This innovative method assumes that only two main factors (power level and wear) affect engine durability or time between overhauls. These two factors are considered as separate and combined with worst case criteria. The wear is assumed to follow a logarithmic law and a formula similar to the Miner's law for material fatigue is used, making it possible to calculate the power-level curve with knowledge of only two points. The wear-curve is also related to elapsed engine cycles. The algorithm is very simple and can be implemented with just a few lines of software code accessing data collected from existing sensors. The system is currently used to evaluate actual residual life of racing engines.

Keywords: Engine, durability, aircraft, algorithm

Introduction

The maintenance schedule is influenced by the wear and tear factor, aircraft engines are kept up based not only on time in flight but also engine running hours. Historically, in the aeronautical world, time between overhaul (TBO) has been expressed in different ways. In some cases engine life was measured by the total number of crankshaft revolutions. This number can be measured with a mechanical or electronic device installed on the crankshaft. In other cases, in some light aircraft for example, it meant simply the total time the engine was running. The specific cockpit instrument is the hour meter. In the automotive field the parameter is the amount of road travelled (expressed in km or miles). The specific instrument is called an odometer. Another parameter is the rate of lubricant consumption.

When this rate surpasses the limit determined 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 dipped below the fuel tank autonomy. In other words TBO was the difference between the moment the aircraft ran out of lubricant and the moment in which it ran out of high octane gasoline. The residual-life-evaluation can be as complicated as one desires, for some vehicles the TBO depends on whether the vehicle is operated in cities or in the country. In F1 racing car engine durability is also affected by the number of times it has exceeded a certain engine speed. This indication is clearly linked to the fact that engine TBO depends on load and piston speed. In some modern automotive engines a sensor signals

when oil has deteriorated and must be changed, but this indication does not have priority over the distance based criteria. The availability of a Full Authority Digital Electronic Control (FADEC) “mini computer” improves TBO criteria with a more sophisticated algorithm. However, since TBO is directly related to engine reliability and aircraft safety, this algorithm should be kept as simple as possible. In fact software complexity deteriorates reliability in an unpredictable fashion. This paper introduces an algorithm developed in racing. This algorithm is very simple and can be implemented in the FADEC with a few lines of code. This should minimize debugging. It returns an on-line measurement of residual engine life for proper TBO scheduling. This paper is set out in two parts: in the first part engine durability and maintenance criteria are discussed, while in the second part the algorithm is introduced.

Engine durability and maintenance

Some considerations about the availability of commercial technology for wear prevention and maintenance

Some years ago the main limitation on durability was due to valve seat and valve train wear. Now massive research on this part of the engine has brought the limit down to the wear of valve guides and piston rings. In some cases bearings and springs are subject 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 material treatments and design-strategy for wear prevention, and on the other side the approach to maintenance. In any practical application preventive maintenance should be performed in order to avoid the risk of engine damage beyond any economically reasonable recovery. Correct maintenance strategy is particularly critical. At the end of WWII, the ideal aircraft piston engine was a “maintenance free” power unit. The only maintenance required was the substitution of fluids and filters on a time, hours or distance basis. The engine was sealed and to be opened only at TBO or in case of failure to pass the routine standard controls. In this case very limited maintenance could be performed in the field by personnel with proper training. Logistics was reduced to a minimum. This maintenance could be performed by virtually unskilled workers. Very limited

equipment was required. After expiration of the manufacturer-specified life or at the first suspicion of “unsafe” operation, the engine was substituted with a new overhauled 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) aircraft and helicopters. In commercial aircraft, where turbine engines are prevalent, highly trained operators perform scheduled inspections and substitute worn out components. This approach makes it possible to substantially prolong TBO. This approach is proved to be more economical than the “closed engine” approach especially for commercial airlines that have well-structured maintenance systems. In fact these very large engines are extremely expensive to replace and to overhaul.

Doubts arise concerning this approach for small organizations and for military use. In any cases it should be considered that durability is a critical factor that needs to be planned and defined before starting the true design phase. Maintenance and overhaul costs should be carefully calculated in order to determine the total cost per every engine flown hour.

That is why design criteria are so important, as well as appropriate choice of materials and treatments/coatings. Another very important aspect is the environmental impact, not only in terms of temperature and humidity level, but also in terms of operating conditions. For example, ultralight aircraft often receive unskilled maintenance or no maintenance at all.

Heat stress is particularly critical, high temperature induces high stress on over-used hyperstatic parts. This condition will be indicated in this paper as “thermal load”.

Rod length, the squared average piston speed, true thermal loading and several other design factors have a well-measured effect on engine durability.

Much research has been conducted on surface treatments in order to reduce friction, wear and to eliminate lubrication. Luckily the new rules in racing require the manufacturer to use the engine for a relative long mileage. This necessity has greatly improved knowledge of design criteria for long lasting piston engines. Plenty of data has emerged from the test bench and from direct racing experience. Far less data are available on low or null power-level endurance. These tests are quite

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 predict engine TBO.

A simplified approach to very low load durability

As previously indicated not much data are available on low load nor on engine durability at idle. "Idle" is particularly critical since engine cooling may prove to be insufficient especially for gasoline engines in a hot environment. Heat overload is particularly present in this case. This type of overload is particularly critical for aluminium alloys due to the high temperature. The engine automatically shuts down when the maximum temperature is exceeded. Other issues regarding oil flow and temperature similarly results in the case of "not-conservative" worst-case design.

This paper takes into consideration engines that are assumed to be correctly designed, tested and installed, so not all of the above cases are considered here. At any rate, a properly set up temperature control system can easily detect any 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 residual life. This algorithm can be easily introduced in the software of the FADEC in a few lines of software code.

This approach is based on the idea 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].

Basic idea and influence of several factors

Basic hypothesis

The engine is well tested and ready for customer use. It wears down in a known and

controlled way. A well designed engine is subjected to progressive wear with increasing blow-by that provokes a progressive increase in the rate of lubricant consumption. Another basic hypothesis is that the technology used in engines is well-known and data is available about long endurance, "low or null power level" or idling condition (see § 3.3).

A further significant condition is overload. No thermal overload or excess speed should take place. In case of overload or excess speed the engine will need to be overhauled.

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 reference temperature measurements are available.

The other components that are subject to wear are substituted at scheduled maintenance stops. This schedule can be based on the residual life calculated by this algorithm.

The estimated engine residual life is derived from the life expectancy of the weakest component or engine coupling. For example in the Merlin 61 engines of WWII a common failure mode was the cracking of the cylinder head. In modern automotive engines it is usually a piston that fails. In both cases the Palmgren-Miner law applies even if the type of stress is not purely mechanical, as shown in reference [11].

The first curve: full load $\ln(\text{HP})$ - $\ln(\text{cycles})$

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

$$\sum_{i=1}^{n_u} \frac{n_i}{N_i} = 1 \quad (1)$$

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 power level. This curve is based on the principle that wear linked to power follows a linear curve in the (HP) - $\ln(\text{cycles})$ diagram [11]. As an example the power curve of a spark ignition aeronautical piston engine is depicted in **Figure 1**.

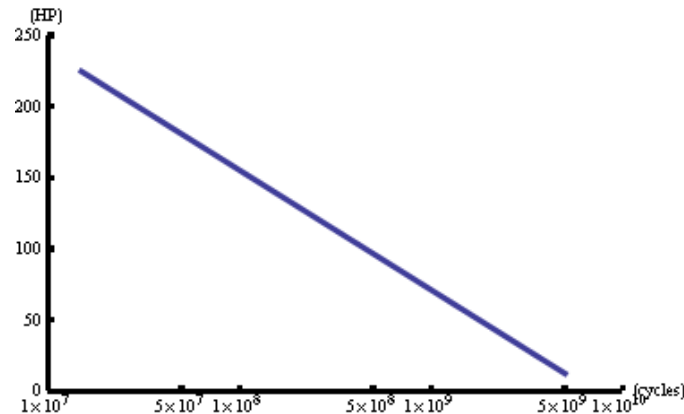


Figure 1 The power curve of an aeronautical spark ignition piston engine.

After a certain number of cycles have elapsed, the FADEC calculates the average power (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

$$n_{u\ a} = \frac{n_i}{N_i} = \frac{1}{3} \frac{6}{0} = 0.0 \quad (2)$$

The residual life then is

$$n_{r\ e\ s} = 1 - 0.0 = 1.0 \quad (3)$$

Eq. (1) is then modified as follows

$$\sum_{i=2}^{n_H} \frac{n_i}{N_i} = 99.5 \quad (4)$$

On the display in the cockpit the residual life is displayed as 99.5 %.

The curve was derived from full load endurance tests. This test is usually performed at the maximum possible power for the engine at the maximum crankshaft speed. The first point of the curve with the greatest possible power output is usually higher than the maximum service power available. In our case it is 120 % the maximum allowed power.

This approach makes it possible to shorten the bench tests and reduce costs. In **Figure 1** the power terminates at 40 HP. Fortunately, endurance at this particular 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 $\ln(\text{HP}) - \ln(\text{cycles})$ diagram of **Figure 1**. However, the engine is rarely run at full throttle. For this reason an additional curve is necessary.

The low (null) load endurance point of the first curve

This data is rarely available. From our own experience, based on very high mileage automotive engines, the following assumption can be made:

A 4T traditional engine with less than 10,000 thermal cycles in the whole life lasts about 1,500,000,000 revolutions. Standard engines are assumed to be built 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 normally use a 1.5 increase instead of 2 to take into account deformation in light alloy engine blocks.

Since endurance at idle is determined by the technology with which the engine is designed and manufactured, **Table 1** gives some useful guidelines for idling endurance [10].

In the first line of **Table 1**, a classic, naturally aspirated automotive engine is considered. The second comes from automotive turbocharged engines. The third line is typical for motorbike replica engines, while the fourth and the fifth come from F1 experience on test beds.

Table 1 Idling endurance guidelines.

Cylinder wall	Piston rings	Valves	Valve seats	Idling endurance [# of cycles]
Cast iron	Cast iron	Steel	Cast iron	1.5×10^{10}
Steel	Bronze	Steel	Steel	1×10^{10}
Nickasil	Steel	High temp. alloy	High temp. alloy	3×10^{10}
Nickasil	Ceramic Coating [2]	Ceramic Coating [2]	High Temp. alloy	3.7×10^{10}
Ceramic Coating [2]	Ceramic Coating [2]	Ceramic Coating [2]	Ceramic Coating [2]	4×10^{10}

It is possible to increase the endurance-at-idle factor significantly by using more durable surface treatments. An example of these treatments is reported in [2].

The key parameter in this case is total wear volume loss. This parameter is affected by many factors, the most important of which is the average mean piston speed.

The second curve: wear related to endurance

An cycle related curve is then introduced, this curve starts from the number of cycles at zero load and uses the principle that wear is related to distance covered by the piston. In fact, according to Archard's law [12-14], the wear coefficient k

relates the volumetric wear rate with the applied load and the sliding distance, given by Eq. (5):

$$Q = k W D S \quad (5)$$

The assumption that W is unrelated to 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. Contact force W is approximately perpendicular to the surface since friction is very low in high speed piston engines. This fact is clearly shown in **Figure 2** where the relationship between load and wear rate of a pin [3] is shown:

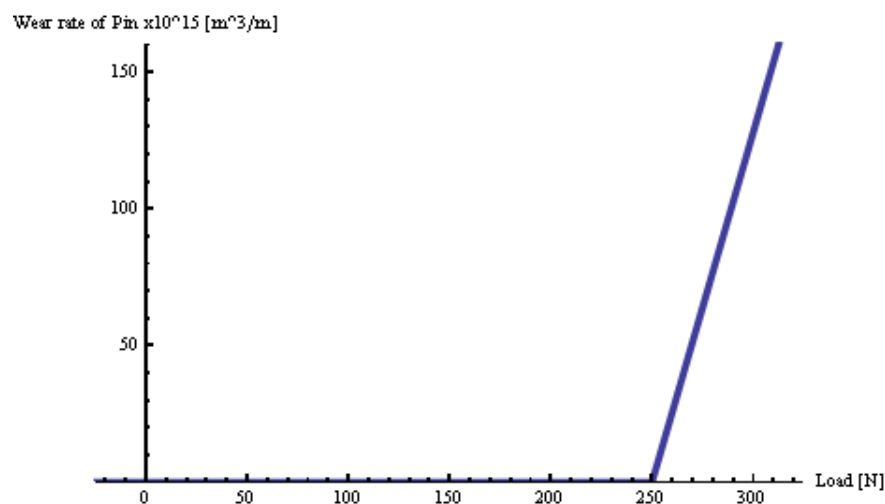


Figure 2 Wear rates of a steel pin as compared to load under a sliding speed of 2 ms^{-1} and lubricated conditions.

In the paper [3], constant wear was measured in the load range of 0 - 250 N. In the 0 - 250 N range wear is relatively independent from load, it is sufficient to calculate the total number of cycles that can be run by the engine. This is the old criteria of hours in light aircraft or cycles in large aircraft [4].

Speed also does not greatly influence wear since the working condition is "full hydrodynamic" see [7]. Once the FADEC has calculated the reduction factor resulting from the power level, the residual life can be calculated based on the number of cycles.

For example, if our engine can run 1,500,000 revolutions and our engine has already run for 254,000 revolutions, the residual life is:

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

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

The thermal cycling parameter [5-7]

Another important factor in engine wear and endurance is thermal cycling. As the engine is started it begins warming up to the operative temperature range. When the engine is shut off, it cools down. As the engine returns to 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 minutes 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 our engine has totalled 331 load cycles with a maximum allowed of 1,000 cycles, residual life will be:

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

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

Conclusions

It is possible to define an algorithm which can optimize maintenance and reliability of a piston engine, by evaluating residual engine life. This can be achieved by comparing two curves: the load curve and the rpm curve. In fact, engine life is conditioned both by 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 also has to be examined.

This method proved to be effective in a naturally aspirated aircraft engine and it may be generalized as an industrial method for better TBO evaluation.

Symbol table

n_i	number of cycles at a given load
N_i	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 no. of cycles at low load [rad/s]
ω_{idle}	angular velocity at idle [rad/s]
Q	volumetric wear of the lower hardness body [mm ³]
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 of entirely.

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