ARPN Journal of Engineering and Applied Sciences

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COMMON RAIL DIESEL - AUTOMOTIVE TO AERIAL VEHICLE CONVERSIONS: AN UPDATE (PART I)

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ABSTRACT

Back to the 1997 when this activity began, it was generally thought that CRDIDs would have completely replaced the piston gasoline engines used in aircrafts within a decade. This fact did not happen for several reasons. This paper tries to individuate these reasons. The more updated solutions to the many problems that almost stopped this application are also introduced. In this first part FADEC related issues are introduced. Torsional vibration control is also briefly discussed.

Keywords: conversion of automotive engines; aeronautical engines; diesel engines.

INTRODUCTION

Aeronautical piston engine should be 99.9999% reliable, lightweight, efficient and very compact. Emissions are not critical: since requirements are not as stringent as in automotive application and rpm is from 50% to 100% all flight long. Propeller/fan noise usually overcomes engine noise, especially in the low frequency field. Automotive engine design is mass production-driven to contain costs. Automotive field of application is mostly in the 0% to 50% Power field. However high torque at low rpm are required. Emission and noise control are the most important requirements. Fuel management and combustion control system are also critical for optimum efficiency. However some points are common: extremely efficient combustion, low maintenance and long TBO (Time between Overhauls). The millions of engines of the automotive field mean trillions of hours (km) run and a gigantic test. Low weight is becoming an important factor also in the automotive market. This means aluminium alloy high pressure pumps, aluminium alloy or compact graphite iron (CGI) crankcases. More compact engines are now available. The conversion of Common Rail turbocharged Direct Injection Diesels (CRDID) is becoming increasingly interesting. Automotive CRDID conversions for general aviation have been a delusion at the moment. The differences between performance required to aeronautical and automotive engines are very large. The project in general and the dimensioning in particular should be aimed to three most important objectives: reliability, compactness and weight to power ratio. The most important factor is reliability. In fact, for example, to obtain the engine certification, the FAA/JAA (Federal Aviation Administration/Joint Aviation Administration) requires the flawless operation for 85 hours at the maximum power, 15 hours at the take-off power and 50 hours cruise. The same reliability level should be attained for the whole engine life. Usually aeronautical power unit have a TBO from 1, 000 to 3,000 hours. This time changes depending on conditions and on the rate of flawless operation.

Efficiency issues

Normal accepted values for CRDID ignition are 1/10 degree and many designers require an order of magnitude less. As air inside the cylinder is compressed it heats up to 600°C before combustion begins. After the combustion temperatures can very briefly reach 4000K. Even if a more conservative 3000 K value is adopted, this means that the "Carnot Cycle reference" efficiency is extremely high (1).

$$\eta_c = \frac{T_1 - T_2}{T_1} = \frac{3000 - 288.15}{3000} = 0.9 \qquad (1)$$

The CRDID p-v cycle, which is more or less the indicator cycle, is very different from the Carnot one. However with such a high maximum temperature the overall efficiency of the CRDID is very high. This is the reason of the very good efficiency of CRDID that can easily exceed 50%. The normal automotive value of 150 gr/HPh (204 gr/kWh) means an efficiency of 41%. For high efficiency the maximum temperature should be kept as high as possible. A high temperature peak is highly desired. In fact engine durability depends on average temperatures, while efficiency depends on maximum temperature.

Just to compare the CRDID with a Gas Turbine, the maximum EGT (Exhaust Gas Temperature) now obtainable for military turbines is 1950K. This value is linked to the maximum power of thrust obtainable, not to the maximum efficiency. To obtain high efficiency the so called "Brayton Cycle", even if Brayton never worked on gas-turbines, should rely on high compression ratio. Compression ratio up to 42:1 can be obtained. The compression ratio of a commercial automotive CRDID is 180:1, since the peak pressure on the indicator cycle reaches this value. Compression ratios up to 330:1 are possible with ad-hoc designed CRDIDs. In gas turbines, the higher the compression ratio the more stages of compression are required. The low efficiency B52 turbojet has a higher trust-to-weight ratio than the turbofan of the latest F35 even if you remove the fan and the auxiliary gearbox. This means that in gas turbines efficiency is paid

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with weight. For power levels from 600HP downwards, the problems of miniaturization and the gaps render gas turbines not competitive with CRDIDs even at the best-efficiency point.

Temperature and pressure are linked together by the Ideal Gas Law that can be rewritten for the V_{cc} (Volume of Combustion Chamber):

$$p_{peak}V_{cc} = RT_{peak} \tag{2}$$

So the higher is the pressure the better. The pressure p_{peak}, that is the maximum design pressure should be obtained for as many engine cycles as possible, in order to keep the engine efficiency at its maximum. By the way this condition improves also combustion efficiency. This result should be kept for any boost, any altitude, any load and any ambient condition. On the opposite, in automotive engines the primary objective is the fulfilment of pollution requirements, that are often in contrast with efficiency. High temperature, in fact, means high NOx, that are severely treated by US and EU normative. With SCR (Selective Catalytic Reduction) the situation has changed even in the automotive field, since high temperatures are favourable to the reduction process.

In the 180 degree compression stroke, the final 30 degrees of rotation adds the same amount of heat as in the first 150 degrees of rotation.

Once it is compressed somewhere near the Top Dead Centre (TDC), the ECU commands a time-defined precisely-measured shot of micron-sized diesel mist under pressures up to 2300 bar. As this finely atomized liquid fuel enters the hot chamber, it quickly begins to evaporate Only at this point the auto-ignition takes place, since liquid diesel is not combustible (not to be confused with “flammable”).

The duration of the combustion depends mainly on properties like cetane and macrophysical properties, such as atomization quality, cylinder temperature, and the final air charge temperature.

A few petroleum based fuels, like gasoline and ether, can auto-ignite at very low temperatures (under 200°C). With these fuels, it would be possible to ignite at more than 50° Before TBC (BTBC). However this would overstress the crankshaft piston assembly.

By boosting just 1.4 bar, it is possible to obtain more than 100 bar into the combustion chamber.

So increasing boost has enormous consequences on ignition timing. Timing is calculated best by angle and rpm than speed. In fact an engine that rotates at 3000 rpm will make 50 revolutions every second. In 0.002s, therefore, the piston goes through 36 degrees.

In that same 36 degree injection event, there may be a 300°C air temperature increase. As fuel is injected, it atomizes and evaporates as it moves away from the injector nozzle. Evaporation also means evaporative cooling. In general, the fuel-air ratio is high near the nozzles tip and low away from it, but the fuel-air ratio does not change uniformly within the cylinder. As the fuel vaporizes into the hot compressed air, it starts to oxidize. As more fuel vaporizes and mixes with air, the number and rate of the oxidation reactions increase in a chain reaction, until the end of the ignition delay period. This time can be evaluated by the "historical" equation from Wolfer (1938) [1] correlation is as follows (3):

$$\tau_{ign} = 0.44 P_o^{-1.19} \exp\left[\frac{4650}{T_o}\right] \tag{3}$$

Equation (3) shows that the delay in exponentially proportional to the temperature. The dependency from pressure is far less important.

In the premixed combustion phase ignition occurs at many locations independently and combustion propagates very rapidly in regions which have fuel-air ratios in the combustible range. At typical full-load operation this initial combustion consumes about 5% to 10% of the fuel used by the engine. Injection continues and fuel continues to vaporize and mix with air, aided by the heat release and turbulence generated by the initial combustion and by the high swirl in the combustion chamber. This quickly generates more gas with the required fuel-air ratio and combustion continues with exponential law. In the mixing controlled phase the remaining fuel should be consumed before partially oxidized droplet meet the "cold" piston wall. It this happens incrustation will narrow the size of the combustion chamber and the fuel "free travel". This occurrence would rapidly reduce engine efficiency and power output.

Automotive design engineers have many objectives, while adhering to government regulated restrictions. Very fast warm up of the engine is a primary objective. The driver will not wait. Heat is taken everywhere, even from alternators, to heat-up the thermal plant in the minimum time possible. For automotive engineers, maximum torque at low rpm is the first requirement, along with acceptable Exhaust Gas Temperature (EGT), minimal noise emissions and then maximized economy/efficiency. The engine should survive for a sufficient number of cycles to this hellish environment. From Alaska’s permafrost winters to Sumatra's high humidity summer, timing must be corrected constantly for smooth operations. Maximum power is seldom required by the car driver. It is and exception. The amount of maximum power is not so important. Maximum torque must be kept to the higher temperatures and altitudes. Power reduction at altitude is normal. It is more important to avoid turbocharger overspeed than to keep power. On the opposite, aircraft engine designers are power minded people. Aircraft engine designers will stop the aircraft for the least time possible for warm up. Only when the temperatures are acceptable, high power at full rpm (take off) will be always required. The take-off run is linearly dependent on thrust. If maximum thrust could not be achieved, the take off will be longer than calculated. Safety will be impaired. Automatic timing corrections for different altitudes and different power setting are also required. Hot restart at altitude and full throttle authority are also important.

In this paper at first we will see a very well done remapping process of an automotive CRDID. Then we will analyze it and we will see what it should be done for an aerial vehicle.

Off design efficiency

The off-design efficiency is affected mainly by intake-exhaust and HPP (High Pressure Pump) efficiency.

At low rpm and low loads the HPP takes a lot of energy from the engine. The net efficiency is reduced. Intake-exhaust automotive ducts are optimized for the maximum torque position. It depends from the engine. Usually it is not the minimum-rpm-maximum-torque point. This will penalize too much the maximum power performance. This is a good number for the marketing. So it is generally located from 2500-3500 rpm. In this condition the engine and its turbocharger are at their best efficiency. However, the SFC (Specific Fuel Consumption Curve) is usually nearly flat from 2000 rpm to 4000 rpm (5% variation). The reason is that the CRDID is a variable mixture engine, with air-to-fuel mass ratio that can vary from 17 to infinity (theoretical): A slight increase over the best value (around 15%) is due to low compressor efficiency and insufficient air mass flow, at speed from 4000 to 4400rpm. Usually this “low” speed is kept for noise emissions. The limit of commercial injection unit is about 6000rpm. The SFC curve is a design choice from the automotive marketing. Flat torque curve and flat SFC mean best drivability. This is the big advantage of CRDIDs. Even with the larger turbocharger that can be used in aerial vehicles, the SFC can be kept almost flat from 25% to 100% of the load in most engines. This means that as fuel is consumed the throttle could be put back. That was Lindbergh’s advice to the B29 crews of the WWII Pacific Theatre for lowest fuel consumption and best survivability.

An example of automotive mapping: the Peugeot 306 HDI map [1].

This car has a 2.0HDI CRDID with 205Nm@1750rpm and 90HP@3200rpm. The High Pressure Fuel Pump (HPFP) has a nominal maximum of 1350 Bar (this consumes up to 5 HP of the output power). The pre-injection injects an approx 1mm^3 of fuel into the cylinder during the compression stroke. This injection reduces the pressure and temperature gradient inside the cylinder before the main injection event. The pre injection, which can be run up to 2000 rpm, reduces combustion noise up to 1dB per cylinder. This also reduces the amount of time it takes for the fuel to ignite under the main injection event. This later is the true Fuel Charge (FC), and it provides the main power stroke of the engine. Injected quantities can reach 51mm3 per stroke at full load. A ‘post injection’ has the purpose cool down the combustion and to contain the NOx. It also occasionally fuels the diesel particulate filter in order to burn off any soot which could potentially clog the filter. The boost pressure of the Garrett GT1546s turbocharger is controlled by a mechanical pressure actuator which opens the waste gate and diverts the exhaust away from the turbine. The ECU controls the maximum amount of fuel injected per stroke as shown in Figure-1.

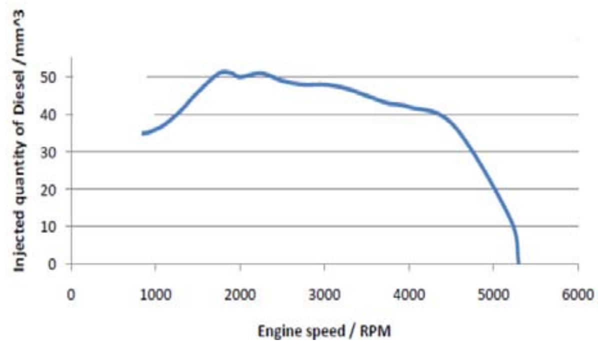

Figure-1. Fuel charge per cycle [1].

As it can be seen the maximum FC is 51mm^3 of fuel per stroke at 1750 RPM. This is the most critical point of the engine, since the torque is at its peak (or very close to it); the peripheral velocity of journal bearings on crankshaft and rods are at the minimum (for the maximum peak). This means minimum film lubricant thickness. The oil pump is rigidly connected to the crankshaft. The lubricant flow depends on the rpm. The pressure should be at its top and the maximum pressure valve should be open. As the engine wears the lubricant leakage is incremented. If the pump doesn’t deliver enough pressure the cooling of the journal may be insufficient. This will lead to higher temperature and less lubricant thickness. The camshaft will also be affected by the oil starvation. The piston is also cooled by oil spray in the backside of the top (opposite to the combustion chamber). This is the design critical point of an automotive engine. Luckily this situation does not happen in aircraft engines where the propeller is not able to require high torque at low rpm.

Looking back to the ECU maps, the FC is also limited with respect to the mass of air entering the engine. This is given by the "smoke map" (Figure-2). This map works the following way: the ECU reads the rpm and the air flow mass (debimeter). From this datum, the maximum value permissible is interpolated by the map of Figure-2. Another map correlates the throttle position to this maximum amount. This amount is the one on Figure-3, the lower of the two is injected.

VOL. 10, NO. 6, APRIL 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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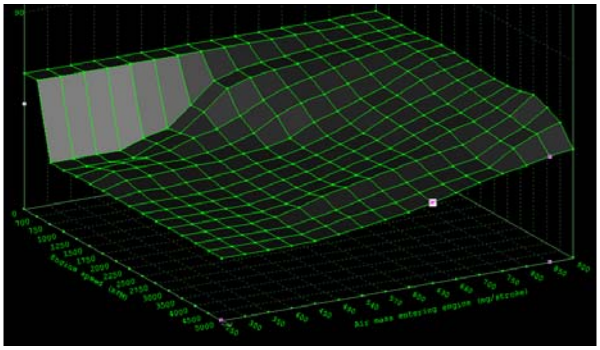

Figure-2. "Smoke" map, rpm-airmass (mg/cycle) vs. fuel quantity [1].

Another map that works on FC is the fuel temperature map; this map limits FC with fuel temperature and engine rpm. This map is controlled by two main factors: emissions and correlation between injected mass and temperature. In fact FC is calculated on rail pressure and injection time with standard fuel temperature. As temperature increases the FC is increased and should be corrected to avoid "black smoke" and emissions out of control. Coolant temperature is also read and FC is reduced by another map. Other maps are available for IAT (Intake Air Temperature) and IP (Intake Pressure=boost pressure). All these maps result to an FC that is the minimum of the "correction set". Since the injector is treated by the ECU (Electronic Control Unit) as an On/Off device, this “map constrained” FC is related to a time of injection. At this point the ECU calculates the timing advance. A minimum and a maximum timing advance are also set and related to rpm with separated maps. Automotive mapping follows the philosophy of maximum performance with emission control and engine durability, the true amount of torque and power output is not important. A best compromise is automatically chosen by the ECU. FADEC aircraft philosophy is reversed since a minimum amount of power should be guaranteed at any cost. If automotive ECU software is to be used, an excellent knowledge of the SW is strictly required. This software is a well kept secret of the ECU manufacturer. The tuner just changes the maps by inserting new values. Even if the tuner is a former employee of the ECU manufacturer, his knowledge is limited to the task he performed on the software, that was stratified with time and it was implemented by several generations of programmers.

The recovery problem

An automotive ECU usually works in this way. Two CPUs are embedded in the ECU in a master-slave arrangement. They are connected to the sensors that are never truly duplicated. The sensors are checked by the CPU for performance. If the required level is not met the sensor is emulated with a curve (map) or a value. For the most important sensors, a red light for “Service” is set on. If the sensor cannot be emulated the power output is reduced. If the sensor is extremely important and “engine safety” is at risk, the engine is fully stopped. These are the recovery strategies, another well kept secret of the engine and ECU manufacturer. This fact implies that the original ECU cannot be used for aircraft conversion, since no control is available on power reduction strategies.

Usually, the automotive manufacturer develops the map on an “ECU for development”. This ECU has its proprietary software. The engine is tuned on the brake or on the car with this HW+SW. After the development phase is finished all the data are handed over to the serial-ECU manufacture that for a few million Euros makes the conversion and prepares for serial production. The prototype-serial ECU, nominally identical to the mass production one, is then approved by the car manufacturer with ad-hoc tests. A car is produced in million of items, while a very successful aircraft engine like the Rotax 9XX series were produced in 40,000 products. The most successful turboshaft (the one also mounted on the Hercules C130) has been sold in 18,000 items. The serial production rate of a successful automotive engine is 4,000 per day. The whole aircraft production would be a 10 days matter. For this reason automotive manufacturer sees aircraft conversion as a nuisance. At best, they supply a certain number of engine “as they are” from the production line. In the other cases the engine should be purchased in the aftermarket or as “spare parts”. After a few years the automotive manufacturer will cease the production of the engine. The modifications of the engine will be on a daily bases, without any interchangeability guarantee. For this reason the automotive engine should be considered more as a source of economic parts than a whole engine. The automotive conversion is then a totally different propulsion unit. A good strategy is to buy a whole “day of production” of the automotive manufacturer. A number from 1, 000 to 4, 000 identical units will then be available.

Advantages of automotive CRDIDs

Automotive CRDIDs from the spare market are extremely cheap and often extreme high quality engines, ready to be prepared for the fly. An inspection is sufficient to individuate undetected production accidents. These engines are thoroughly controlled for main tolerances during the production process. It is possible, from the manufacturer database, to access to an impressive number of measurements on every single engine, while manufacturing processes are controlled through samples on part batches. Certification authorities require a whole control of the main tolerances. Apparently, this technique is a good idea, but the disassembly and manual assembly of the already CNC (Computerized Numerical Control) assembled engine is not so convenient. It is far better to remove the covers for a visual inspection and to check the cranking torque to have a very good idea of the engine quality.

Aircraft CRDIDs that come from the automotive conversions have also the advantage that “spare” and used engines are available o the market. For various reasons engines tend to survive to the car. Modern CRDIDs are normally conceived for a useful life of 250, 000 km (155, 000 mi); this usually means approximately 9, 000h. If your target endurance is 3, 000h a used car with about 200, 000km should be chosen. It is true that car use is very different from aircraft use, but a worn engine is better than a new one in any case. This engine can be tested as it is, but normally it is better to change the injectors, since their replacements should be done every 150, 000km for optimum performance. The original electronic can be installed and the engine can be tested on the brake, a slight reduction of maximum output power is normal (about 10%). Many data can be retrieved from this tests that can be then used for the aircraft conversion. The worn engine is the best choice for the mapping process, since it is close to our worst "aircraft condition". During the certification process a first reduced life is initially assigned in the "type certificate". A typical initial "certified" life is 500h. As flight experience is done this limit is progressively extended to the design target that, in our case, should be 1,500h for helicopters and 3,000h for aircrafts. It is also possible to implement an algorithm in the FADEC that calculates the residual life depending on the load history, since the hours/cycles approach is obsolete.

Hardware for aerial vehicles

The automotive engine is then stripped of all the accessories unnecessary for aerial vehicles. A new wiring and a FADEC (Full Authority Digital Electronic Control) are installed in place of the original wiring and ECU. A new manifold, exhaust and a new turbocharger also often installed. The FADEC may be derived from the sporting automotive field or specifically conceived for aircraft/helicopter application. In both cases it comes with a cable to a Personal Computer (PC) and specific programming software for engine tuning or mapping. Sensors and actuators are changed or updated in order to have the necessary reliability. Generally the rail pressure sensor(s) and the pressure actuator(s) on the rail are kept. However for this later it is necessary to check if, in case of failure, it remains closed. An additional pressure limiter valve may be added to the rail.

A duplicated rpm sensor on the crankshaft is mandatory. The sensors should have software diagnostic system in order to check whether they work properly. Another sensor that should be duplicated is the throttle, since it is not easy to land with "full throttle" and this is the "recovery option" for throttle-sensor failure.

PSRU and crankshaft torsional vibrations

Normally a PSRU (Propeller Speed Reducing Unit) should be installed. This is normal for high performance engines since WWII. The last high performance direct crankshaft-propeller installations were the great radial engines from Pratt Whitney and Wright. The Continental and Lycoming piston engines are pre-WWII design concepts. Both direct and PRSU propeller installation share torsional vibration problems that may easily destroy the engine at start or at stop. They should be addressed by specific studies. This problem is common to the automotive application. In CRDIDs an elastomeric torsional vibration damper is always installed on the pulley for auxiliary. This is normally a poly-v pulley. This damper works is the 2500-3500 rpm range. If correctly tuned it lasts the engine. In a few units, the common mistake to install a perfectly tuned elastomeric joint was made. In this case the damper works at its best with its resonance frequency centered in the crankshaft natural frequency. However the rubber is extremely stressed and it does not last long. A larger "less tuned" damper should be used instead. In aircraft application it can be removed and the frequency can be avoided by the FADEC software. This is a possible strategy, but in this case a variable pitch propeller is mandatory.

The crankshaft vibration calculation should be made with the Lloyd method, that comes from the British WWII experience and it is described in the Ker Wilson's book. This is mandatory for FAA/EASA approval. A decoupling joint is necessary in most cases.

The decoupling joint history

Decoupling joints have always been a difficult design issue. In the old WWII engines from RR, Daimler Benz and Jumo, a slim connecting shaft was used. Like Armored Vehicle torsion bars, it was carburized, quenched, decarburized and shot-peened for fatigue. During WWII it demonstrated not to be a weak point. In our CRDIDs, the authors used helical springs and rubber joints. Both solutions proved to be critical. The rubber joint is normally tuned around 200 rpm. This frequency is not far from the starting one (300 rpm). If the starting takes long times the joint is much stressed. A maximum starting time is then to be set for joint survival. An even worse condition is at stop. The FADEC cannot control the stop of the engine below 300 rpm. In this case the rpm sensor on the camshaft should be used, high vibrations arise and the signal is not clean enough to be read. The fuel flow is then interrupted and the engine stops. However the CRDID has a high compression ratio. The braking pressure and torque on piston for the 2.0 liter Fiat Multijet engine can be easily calculated. Assuming the ideal adiabatic transformation, the peak pressure is given by (4)

$$P_{peak} = \frac{P_{boost}(V_{unitary} + V_{cc})^k}{V_{cc}^k} = P_{boost} r^k = 4.5 \times 10^6 [Pa] \tag{4}$$

This means a TDC (Top Dead Center) force on piston of about 6000N. It is also possible to calculate the variation of pressure with the crankshaft angle α (5)

$$P(\alpha) = \frac{P_{boost}(V_{cc} + V_{unitary})^k}{(V_{cc} + s(\alpha) \times A)^k} \tag{5}$$

With

$$s(\alpha) = \frac{st}{2}(1 - \cos(\alpha)) + l(1 - \sqrt{1 - (\lambda \times \sin(\alpha))^2}) \tag{6}$$

VOL. 10, NO. 6, APRIL 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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The "ideal" braking torque for the single cylinder is (7)

$$T(\alpha) = P(\alpha) A \sin(\alpha) \frac{st}{2} \tag{7}$$

This curve for the 2.0 Fiat Multijet engine is shown in Figure-3.

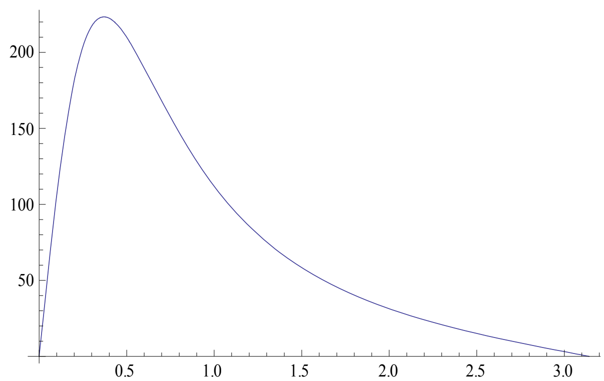

Figure-3. "Ideal" braking torque [N] with crankshaft angle α.

Since the propeller inertia is high, this torque will act on the rubber joint that is in the resonance point. The torque magnitude is then amplified by a factor depending on joint damping. This fact means that the joint will be stressed with a Torque=242 Nm in the "ideal" case. The true case will be less, but with the blowby at the minimum (hot engine) it is indeed a very high load. The result is a sudden stop of the propeller, which means a shock load with further amplification. The result will be high stress on PRSU, joint and propeller. Cracks at the propeller bolt holes may be found.

Figure-4. An early installation of the CRF 1900jtd-8V on a propeller-test-bench (2001).

In the very initial development stage that was carried out with CRF (Centro Ricerche Fiat) at the University of Bologna site in Forlì (Figure-4) a rubber joint was used. This solution was later discarded due to EASA requirements. However, in the many CRDID ultralight applications that were made with commercial rubber joints, no failure of the rubber part was ever encountered. The only failures were on the bolts and on the center joke. These failures were due to fatigue of poor quality components. The quality of steel and the finishing level of the parts were the corrections applied. Later the yoke was eliminated and the single joint solution was adopted. The main difference from Figure-4 is that the joint cover was air vented for better cooling and pre-flight inspection (Figure-5).

Figure-5. Naldini's trike with CRDID and double rubber joint (2009).

The latest solution is to use a carbon clutch with an integrated helical spring damper. This clutch is controlled by the FADEC. At start-up the FADEC disengages the clutch and the engine is started with the propeller at idle. After the engine is started the clutch is engaged and it is kept in this position all the flight long. After landing and taxiing to full stop, the "engine-stop procedure" is started. In this procedure the engine is brought to about 1000 rpm and then the clutch is disengaged by the FADEC. The engine is then fully stopped.

The clutch makes it possible also to refuel the aerial vehicle without stopping it. In this case, the clutch is opened by the FADEC (an input from the pilot is required) and a manual override is applied for safety reasons. The aerial vehicle can then be refueled with the diesel fuel. This is particularly useful for CRDIDs. In fact thermal cycling is a critical endurance factor for this type of engines.

CONCLUSIONS

For successful automotive to aerial vehicle CRDID conversion a clear analysis of constraints and objectives is to be performed.

CRDIDs are fully controlled by FADEC software. In this paper only the most important variables and sensors have been introduced and an example of automotive software implementation has been briefly discussed. General criteria of aircraft injection mapping have been discussed, along as some hidden hints that are not reported on books. Very careful SW control should be implemented in order to avoid serious flight problems. In aerial vehicles the primary objective is safety. For this reason power reduction strategies should be applied by the PF (Pilot Flying) and not by the FADEC software as it happens in automotive CRDIDs. Torsional vibration problems have also been investigated. A few, thoroughly tested solutions of this problem have been briefly described.

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Symbols

Symbol	Description	Unit
P_{peak}	Peak pressure in combustion chamber	Pa
P_{boost}	Min pressure in cylinder	Pa
r	Compression ratio	-
$V_{unitary}$	Cylinder displacement	m^3
V_{cc}	Combustion chamber volume	m^3
k	Adiabatic constant	-
s	Piston run (from TDC)	m
α	Crank angle from TDC	rad
st	Stroke/2	m
A	Piston area	m^2
l	Rod length	m
λ	l/(st/2)	-