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PRELIMINARY OPTIMIZATION OF A COMMON RAIL DIRECT INJECTION DIESEL ALTERNATIVE TO THE AE2100 CLASS TURBOSHAFTS

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ABSTRACT

It is shown that a CRDID (Common Rail Direct Injection Diesel) turbo compound design is a highly over constrained problem. Very few options are available to the designer, even from the metallurgical point of view. The process of the preliminary design is fully described and the preliminary performance evaluation is fully described. A comparison with the original turbo shaft installation of a Hercules C130J aircraft is performed and the results are analyzed. The CRDID turbo compound seems an extremely convenient option since it can halve the fuel consumption, with increased safety and reduced logistical problems. CRDID emissions, with SCR (Selective Catalytic Reduction) may easily reach the automotive Euro 6 standard.

Keywords: Common Rail Direct Injection Diesel (CRDID), AE2100.

INTRODUCTION

The possibility to design new CRDIDs of the Rolls Royce AE2100 class for aerial vehicle applications is introduced in this paper. The multivariable engine design problem proved to be overconstrained. At the beginning a Genetic Algorithm multivariable approach seemed to be feasible. A spreadsheet generated engine can be easily designed with modern CAD software. Preliminary design can be embedded in the process to avoid to generate "impossible" design. The objective function is to limit the propulsion plant weight. So, everything seemed to be at hand. However the process proved to be overconstrained. Very few choices were left. In fact, in order to have a feasible design, the process should start from commercial CR injectors. The number of injector per cylinder defines the piston bore and geometry. In fact in CRDIDs the bowl shape for the combustion chamber is the best choice. The size of the combustion chamber and its geometry being dependent from the injector. The bore size should be kept at the minimum value possible, in order to minimize engine size and weight. The stroke again depends on the injector. In fact the mean piston speed is an initial design choice to reach the desired TBO (Time between Overhaul). At this point only the number of cylinder is to be chosen between a restricted set of possibility: 4, 6, 8, 12 or 16 cylinders power unit may be selected. Piston engines are modular design based on the single cylinder unit. After the piston geometry is defined and approximate indicator cycle can be calculated. At this point a preliminary 3D design of the head and of the crankshaft can be implemented. An iterative process of virtual simulations is then to be performed on this design; that is optimized to the possible feasible limit of simulations; that are limited by computer speed. At the end the design of the prototype will output the necessary data do decide whether it is convenient to manufacture the prototype and develop the project. For sake of simplicity this V12 version of the CRDID was called "VD007".

The end of the turbine era: piston engines strike back

With off-the-shelf modern CRDIDs, in the range below 1,000HP, it is already possible to reach power to weight ratios of 4 (HP/kg) with specific fuel consumption down to 140 gr/HPh. This means that most of small general aviation aircraft and helicopters, manned and unmanned aerial vehicles can already be powered with CRDIDs. With updated SCR technology it is possible to reduce emissions down to the equivalent of automotive Euro 6 without penalties in performance. Another main advantage of modern CRDIDs is the possibility to run with "heavy" diesel automotive fuel. This means extremely reduced fire hazard and the possibility to purchase and stock a far less volatile fuel. For the military it means the extension of the single fuel concept to helicopters and medium transport aircraft, of the class of the C130J. In the <5,000HP field, it is already possible to have diesel engines with power to weight and power to size comparable to turboshafts. In the next few years it will be feasible also to develop extremely high power diesels for High and Low bypass dieselfan with power up to 40, 000HP and with weights and dimensions competitive with actual and future turbofans for future airliners and future fighters. It is worth to remind that the diesel common rail engine is now the more efficient thermal machine in the world. 140 gr/HPh means and efficiency of more than 42% that is the efficiency of a good basic thermodynamic cycle for large electrical power plants. It is also possible to improve this value with turbocompounding as introduced in other papers [1]. The diesel common rail performances in terms of fuel consumption in off design conditions are far better than any other thermal machine or plant, large electrical power plant included. It is perfectly possible to have the same excellent efficiency from 50% to 100% power output that is the range of interest for aerial vehicles. The CRDIDs that have the problem of overcooling during idling, this means that the engine dissipates so few energy that it is difficult to keep it warm enough. For this reason the aeronautical CRDID has to be designed a tuned in such a way to keep it warm during descent and to reduce the warm up time after a cold start. The piston engine cooling energy can be conveyed into a static motor that converts heat into thrust. This is the Meredith effect that was implemented in almost every piston engine propelled aircraft of WWII. This effect is still used in formula 1 racing cars. The residual exhaust kinetic energy can be used for additional thrust by the ejector exhaust. This means a complex turboplant with the relative reliability issues. Reliability and manutability are the real challenges. Turboshafts have had 60 years of intensive and very well financed research. Turbines are "tricky" machines with many problems that have been solved through the year to the impressive figures of today. Nearly 5000h TBO with 99.9999 reliability are true figures for turboshafts.

CRDIDs with their research limited to the automotive field and their history of 10years can not compete. However CRDIDs advantages are so important that enormous advantages can be obtained in terms of environmental impact, economy and safety.

SCR (Selective Catalytic Reduction) make it possible to keep the Euro0 performances even with the automotive Euro6 specifications.

Another important issue is that development costs are not huge. It is perfectly possible to replace the original turboshaft powerplant with a new automotive-derived CRDID one with less than 1, 000, 0000€ for the prototype in the Agusta A109 helicopter.

The purchase price of a CRDID prototype and a certified mass-produced turboshaft are almost the same. This is due to the fact that CRDID come from the extra-cheap automotive field, where numbers are of the order of millions. For example the extremely popular Allison T56 turboshaft was produced in 18, 000 items. The FIAT 1, 300jtd CRDID, that is a normally successful automotive engine, has been already produced in more than 4,000,000 items. The V007engine can be produced in various different versions, from the prototype 4 cylinder unit to the V8 and V12. This is due to the modular design of the piston engine.

The idea is to design a CRDID competitive with the Rolls-Royce AE 2100, that outputs more than 4,000HP at sea level, weights about 8,000N and has an SFC of 0.4 lb/sHPh (243 gr/HPh).

New engine design specification

CRDID have a constant output power and approximately a constant output power up to the recovery altitude. From that level on the maximum power and the throttle control be reduced. A second characteristics altitude is the "full throttle only" one. From this altitude upwards, the engine will not recover power if throttle is reduced. The third altitude is the "no flame". At this altitude the engine will not ignite anymore, since pressures and temperature in combustion chamber are too low for auto combustion. A fourth altitude is the hot restarting altitude.

The Rolls-Royce AE 2100 will have a power output with altitude similar to the curve in Figure-1 (Model 250 C20R).

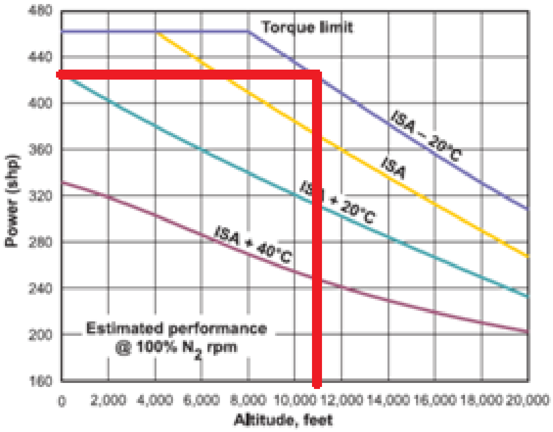

Figure-1. Rolls Royce 250 C20 R, sHP at take off.

As it can be seen the air density is important for turboshaft output power. Rolls Royce declares the AE 2100 "flat rated", this may mean that the FADEC limits the fuel output to keep power constant at any temperature offset between ISA-20°C and ISA+20°C. It is then possible to make a horizontal line that reaches the ISA-20°C and to find the "recovery altitude" of our turboshaft, in this case about 11, 000ft (3350m) with an air density of 0.87. From this point on the engine will lose power with air density. So the AE 2100 will have at 22,000ft about 2550HP (1):

$$P_{altitude} = \frac{\rho_{altitude}}{\rho_{reference}} P_{reference} = \frac{\rho_{22,000}}{\rho_{11,000}} P_{reference} = 2550 \qquad (1)$$

It is possible to think to use a turbocompounding system for take off [1], so our diesel may output only P_{target}=2600HP (1900kW) for cruise at 22, 000ft. In this case the recovery altitude will be 30, 000ft [1].

Power obtainable, CR injection considerations

In this section we evaluate the maximum power achievable focusing only on considerations related to the mass flow rate allowed by a commercial automotive CR injector. At the current state of the art modern injector can easily reach ***d***=140 mm³ of overall injection volume per cycle. For this type of injectors, the maximum allowed crankshaft speed is n_{max}=6, 000rpm. Assuming an overall engine efficiency of η=0.42 (140 gr/HPh) and a lower calorific value K_i of our fuel of 10,000 kcal/kg, it is possible to calculate the maximum FC (Fuel Charge) each injector can output for every cycle (2):

$$FC = \frac{d \times \rho}{100^3} \approx 1.44 \times 10^{-4} \tag{2}$$

where ρ=800 [kg/m^3] is the fuel density. It is then possible to calculate the maximum power output for each injector (3). The number of combustions is equal to half the number of rotations per minute, so the number 2 should be added at the denominator.

$$P_{injector} = \frac{K_i \times \eta \times FC \times n_{\max}}{2 \times 60 \times 1000} \approx 100\,[kW] \tag{3}$$

In order to obtain the required power output it would be necessary to use at least $P_{target}/P_{injector} \approx 19$. Since a V16 is the maximum reasonable engine for this application we would have to turn to larger injectors. However, for pure dynamic reasons, the larger the injector the lower is the maximum rpm allowed to the crankshaft.

Another consideration should be made about injectors. In aerial vehicle applications dual injection is highly recommended due to increased reliability of the system. A dual injection was then designed and patented for this specific application. The ideal engine is then a classical 12-cylinder unit with two injectors per cylinder.

Piston design

For our new piston, the combustion chamber was taken directly from automotive field. Bowl geometry, in fact, depends only on the injection system. It is generally preferred to keep the swirl rate as large as possible. The injector outputs up to 8 sprays that cut the hot air inside the cylinder. As the sprays burn inside the bowl-shaped chamber they tend to slow down. If the unburnt fuel reaches the bowl wall or the cylinder liner, it will reduce the bowl size and it will progressively decrease the power output. Bowl shape and size are then critical. A possible piston design is shown in Figure-2.

Figure-2. Two bowls piston design.

CR injection precision is a guarantee of a simultaneous injection of the two injectors an it avoids undesirable asymmetrical loads on the piston in the combustion phase. In any case since pressure runs at the speed of sound inside the combustion chamber, pressure unevenness will be smoothened in very short time. In fact for the ideal gas equation (4) holds. In case of a temperature of 2500K, with k=1.2 and R= 287.0

$$Mach = \sqrt{kRT} = 2800\,[m/s] \tag{4}$$

In our case the bore can be as small as D=108mm so the time for a shock wave to travel it is:

$$t = \frac{D}{Mach} \approx 38[\mu s] \tag{5}$$

It is necessary to keep the bore as small as possible since the true compression ratio depend on the bore diameter. In fact it is necessary to keep a gap between the piston and head. As a tentative value this gap ***g*** is around 1 mm.

On the other side the stroke is defined by the mean piston speed. This value is about ***cm***=14 m/s for high speed diesels, so

$$stroke = \frac{30 \times cm}{n_{\max}} = 70[mm] \tag{6}$$

It is then possible to calculate the true compression ratio (7) (8) (9).

$$r = \frac{Vcc}{Vcc + Vc} \tag{7}$$

$$V_{cc} = 2 \times V_{bowl} + \frac{\pi D^2}{4} \times g \tag{8}$$

$$V_c = \frac{\pi D^2}{4} \times stroke \tag{9}$$

In order to start the engine even in the coldest condition (ISA-50°C) it is necessary to have at least ***r***=12.5. In order to take into account of engine wear, a minimum value for ***r*** of 13.5 is advised.

Indicator cycle

A first tentative indicator cycle can then be calculated. A possible method is the one indicated in [2]. It is possible to assume the following input data (sea level ISA+0°C): intake pressure Pi=6.1 bar, intake temperature **Ti**=223.15K exhaust pressure **Pe**=6.1 bar, **Te**=850K, volumetric efficiency η_v=0.79, mixture ratio **a**=22, **r**=14:1 (calculated). This is the worst condition: the engine at take-off. In cruise the intake pressure will be reduced down to **Pi**=2.5-3.5 bar and the peak chamber pressure will be accordingly downsized.

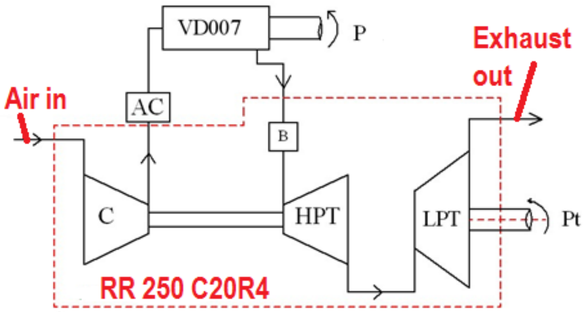

Figure-3. Turbocompound at take off.

At take off (Figure-3) [1] the compressor **C** of the gas-coupled turboshaft outputs air at the pressure ratio of 6.1:1 (possibly from one of the Rolls Royce 250 turboshaft family). This compressed air is diverted to the CRDID (VD007) through the aftercooler AC that reduces manifold temperature to Ti=223.15K. The CRDIDs outputs the hot exhaust at Te=850K to the combustion chamber B of the turboshaft. The exhaust is then reheated by the RR250 burner up to the required temperature and sent to the RR250 turbines (HPT+LPT) that recover power for the propeller. In this way it is possible to increase the piston engine output power up to 25%. In our case the take-off power would be $P_{tot}=P_{target}+P_{turboshaft}$=2, 600*1.25=3, 250HP. By using the method of [2], it is possible to obtain a possible indicator diagram at take-off (Figure-4).

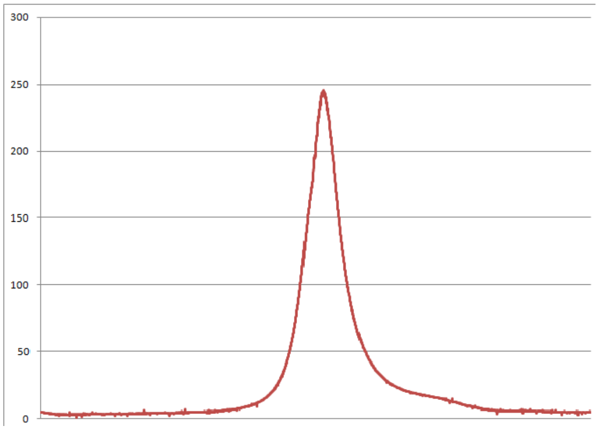

Figure-4. Indicator diagram at take off. The peak pressure of about 250bar is at +14 ATDC.

The cruise condition will be much less critical, since the Pi would be limited between 2.5 and 3.5 depending on the effective volumetric efficiency, that value it is difficult to estimate and depends from several factors including pi, Ti, pe, Te and Re. Figure-5 shows the cruise condition. The burner B of the turboshaft is off.

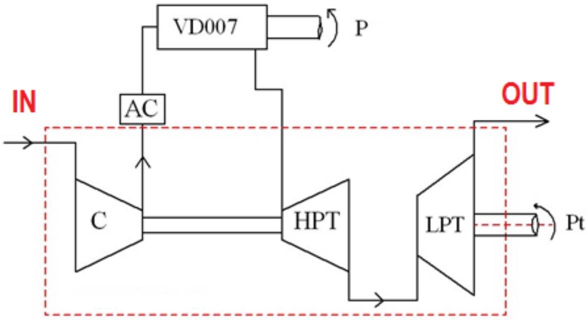

Figure-5. Turbocompound on cruise.

It should be clear that, for the reason explained in [3], the maximum design peak pressure will be much higher (around 300bar).

Pme compatibility

A compatibility check of the mean effective pressure **Pme** should be made before beginning the first preliminary design. From the maximum CRDID power it is possible to calculate the maximum torque T (10), which for aerial vehicles is a 5% increment of the $\mathbf{P_{max}}$ one:

$$T = 1.05 \times T_0 = 1.05 \times \frac{P_{max}}{\omega_{max}} = 1.05 \times \frac{P_{max} \times 30}{\pi \times n_{max}} = 1.05 \times \frac{2600 \times 0.735 \times 30}{\pi \times 6000} \times 1000 \approx 3200 [Nm] \tag{10}$$

The Pme can then be calculated with

$$Pme = \frac{T \times n_{car}}{V_d} \times 2\pi = 5.2[MPa] \tag{11}$$

that is a very high value, but still compatible with CRDIDs. Just to have an idea, the commercial 500Nm 4-in line 2 liter BMW CRDID has a Pme at maximum torque of about 3.2 MPa. This value is achieved with a aluminum alloy head.

In our case we will use steel or inconel pistons and a better, more expensive technology, for the heads. In the BMW case the peak combustion chamber pressure is below 200bar.

Virtual prototyping

Before making any further evaluation, it is advisable to make an initial tentative, simplified CAD model of the engine. This will make it possible to design the intake ducts and to implement a virtual 1-D gas exchange simulation program model of the engine. From this model it will be possible to have more "precise" data for the preliminary design. The parametric 3D preliminary CAD can then be modified according to the 1D flow model in an interactive way to obtain a final design for the prototype. Thermo-structural (Finite Element Analysis) and CFD (Computational Fluid Dynamics) simulations can then follow. The virtual 3D prototype will be refined until the production of the prototype. This procedure is interactive and may take to the infeasibility of the design. For this reason and to cut down development and production costs, engines are normally derived from "old" ones. Unfortunately, in our case, the last piston engines of this size were conceveid during WWII. This "age" is more or less the archeology of modern piston engines.

Design choices

Due to overcooling at low load and on descent, blow-by control and Meredith effect additional thrust, water cooling is mandatory for this type of engines. In our case three different solutions are available: the RR Merlin V12 engine, that is the "father" of most Formula 1 naturally aspirated engines, the Daimler Benz DB 605 "inverted V12" engines and the Lycoming flat engines (O-1230). The RR Merlin engine has the wet liner design, that may give, in time, leakage problems. The Lycoming flat engine is wide and it cannot be installed in the Hercules C130 nacelles. So the choice fell on the Daimler Benz DB605 (Figure-6). Since this new engine needs a speed reducer the "inverted V12" solution was discarded due to a more complicated lubrication system.

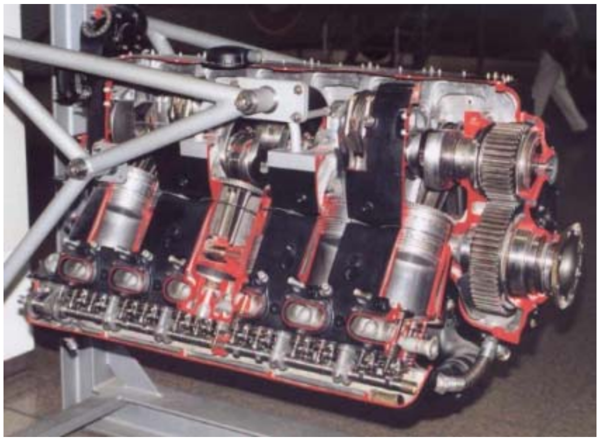

Figure-6. The DB 605 inverted V12 WWII engine.

Fundamentally the engine is composed by four parts, the two cylinders block with integral heads, the crankcase and the PSRU (Power Speed reducer Unit). This architecture will be kept in the new engine. In the DB605 steel cylinder barrels were screwed and shrunk into cast aluminum alloy cylinder blocks. These dry liners projected beyond the block, providing attachment by means of threaded rings which pull the liners against the finished face of the crankcase.

Figure-7. Transparent image of the 4 valve V12 engine.

This feature helped to save weight and to reduce dimensions, by not requiring hold-down studs, and avoided the possibility of distortion. This solution brought several cooling problem for the DB6xxx engine that were partially reduced by limiting the liner thickness. A better solution was used by Ferrari for the Formula 1 turbocharged engine of 1981. In this case the liners are interference fitted into the aluminum alloy block. A brazing alloy may be also added during assembly to improve cooling. Steel pistons and liners are a very good solution to control blow-by. However steel cylinders are heavy and the inertia loads have to be reduced by using titanium alloy rods. The short stroke and large journal bearing diameters help to reduce torsional vibration loads on the crankshaft. The CFD tests on the head advised the use of a 4 valve per cylinder solution (see Figure-7).

The original hold down stud solution of Figure-7 with head-cylinder gasket was discarded afterwards.

The crankshaft can be copied from the original DB605 one. This massive crankshaft can be manufactured by CNC machining (Figure-8). Modern steel like the AISI 300M can be used. Tungsten high density masses can be used for accurate balancing. The large pins are hollow and aluminum alloy bushings should be inserted in the holes for lubrication. A preliminary design of the complete engine assembly is depicted in Figure-9.

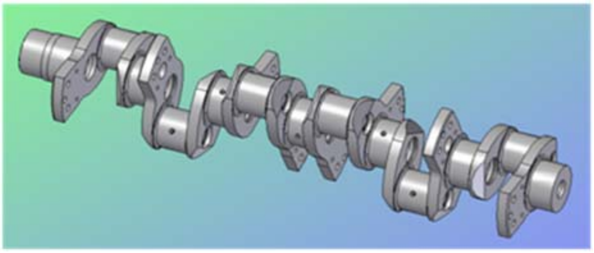

Figure-8. The "DB 605 style" crankshaft.

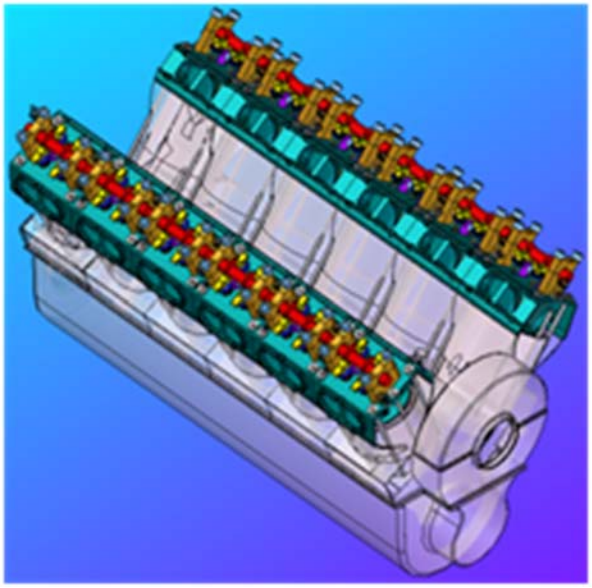

Figure-9. The first tentative of "complete" assembly of the VD007.

A preliminary installation study of the VD007 engine power plant on a Hercules C130J aircraft is depicted in Figures 10, 11and 12.

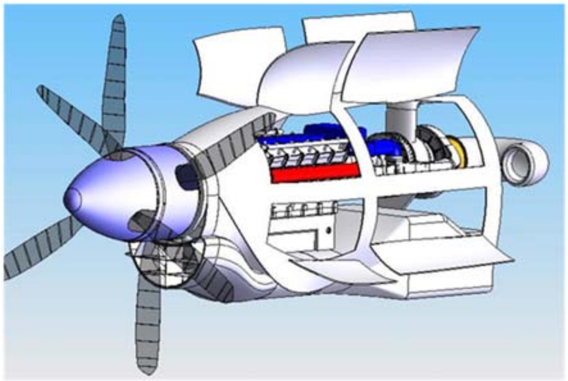

Figure-10. Hercules C130 nacelles with VD007 turbocompound installed.

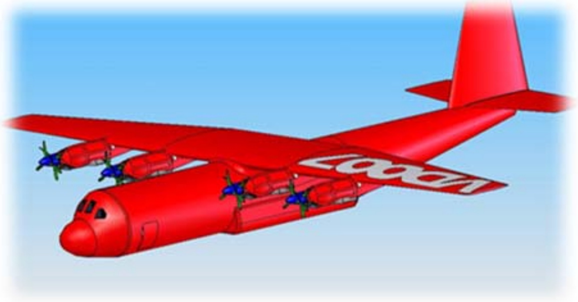

Figure-7. VD007 turbocompound installed on the Hercules C130.

As it can be seen from Figure-11 the powerplant has dimensions compatible with the C130J aircraft. Propellers should require an ad hoc optimization. At this point it is possible to make a first comparison of the two powerplants, just to evaluate the feasibility. It should be noted that aircraft installation of CRDIDs differs significantly from the automotive one. In aircrafts. the frontal section of the powerplant is critical. As it can be seen, further work should be made to reduce the VD007 turbocompound frontal section (Figure-10). If it possible the propeller axis should be moved upwards. The Meredith effect duct below the powerplant is overdimensioned and not well integrated in the nacelle. The dynamic air inlet should use (a) NACA duct(s) and a plenum chamber. A preliminary comparison between the two powerplants is shown in Table-1.

Table-1. Comparison between turboshaft and CRDID turbocompound.

	RR AE 2100D3 (Hercules C130j)	**VD007 turbocompound**
Power	4000 HP	3250 HP
Mass	872 kg	860 kg
Width	1050 mm	739 mm
Height	1490 mm	1460 mm
Length	3149 mm	3007 mm
SFC	243 gr/HPh	126 gr/HPh (cruise) 166 gr/HPh (take-off)

As it can be seen the CRDID SFC is nearly half the one of the turboshaft. Even if the takeoff power is lower (-12%), the amount of fuel that has to be loaded is more than halved. In fact, the excellent off-design efficiency of the turbocompound makes it possible to reduce throttle as the aircraft weight is reduced by fuel consumption. In this way the aircraft always flies in the best global efficiency condition. The fuel capacity of the C130J is 9,680 US gal for a total of about 30,000 kg of fuel. The maximum TOW (Take Off Weight) of the C130J is 70, 307 kg, so with half the fuel it will become 55,307kg. Since the take-off run goes with the inverse of TOW^2 and proportionally with the Propulsion power, the TOW with the CRDID turbocompound would reduce the take-off run of (11):

$$TO_{run\_reduction} = \left(1 - \frac{TOW^2_{CRDID}}{TOW^2_{turboshaft}} \times \frac{P_{turboshaft}}{P_{CRDID}}\right) \times 100 \approx 20[\%] \qquad (11)$$

In this evaluations we did not take into account the additional thrust of the Meredith duct that will be important especially in cruise.

CONCLUSIONS

The design optimization of a CRDID turbocompound to replace the RR 2100 class turboshaft proved to be an overconstrained problem. Very few design variables are really available. A preliminary design of a turbocompound was then easy to implement and comparative evaluations can be done. Due to the huge savings of the CRDID option, the development of such a project in this power range seems to be highly convenient. In fact this type of engine has a unitary selling price of over 3,000,000 USD and has a very large market, with production numbers over the 20,000 units. Even higher incomes come from the spare parts market due to the high number of flight hours per year. The development of a CRDID of this type will unavoidably have problems of reliability, so it is convenient to start from an engine for military transportation, where the possibility to use the diesel fuel is highly convenient from the logistic, safety and storage point of view. However, development costs of the turbocompound engines are not high, when compared with an entirely new turboshaft. In fact a lot of data are already available from the automotive market and from the automotive-to-aircraft CRDID conversions. This CRDID turbocompound may use the old and reliable design of the RR 250 turboshaft family to increase the inlet pressure to the CRDID and to recover energy for Take Off (TO). On a C130J aircraft the TO run would be reduced of 20% and the fuel consumption would be halved in a standard flight with maximum TOW.

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Symbols

Symbol	Description	Unit	Default value
$P_{altitude}$	Shaft output power at altitude	HP	
$P_{altitude}$	Nominal shaft output power	HP	
$\rho_{altitude}$	ISA+0°C air density at altitude	kg/m^3	
$\rho_{reference}$	ISA+0°C air density at reference altitude	kg/m^3	
n_{max}	Max crankshaft speed	rpm	6,000
η	Overall CRDID engine efficiency	-	0.42
Ki	Lower specific calorific value of fuel	kJ/kg	10,000
d	Maximum volume injected x cycle	mm^3	140
ρ	Fuel density	kg/dm^3	0.8
$P_{injector}$	Maximum output power for an injector	kW	
T	Average combustion chamber temperature	K	
R	Ideal gas constant	J/(kg K)	287
k	Adiabatic index exhaust	-	1.2
r	True compression ratio	-	
g	Piston to head cold play	mm	1
cm	Average piston speed	m/s	14
D	Bore	mm	
V_{bowl}	Bowls volume	mm^3	
V_{cc}	Total combustion chamber volume	mm^3	
Ti	Intake manifold temperature	K	223.15
Pi	Intake manifold pressure	bar	
Te	Exhaust manifold temperature	K	
Pi	Exhaust manifold pressure	bar	
η_v	Volumetric efficiency	-	
a	Air mass/fuel mass	-	
P_{target}	Design CRDID output power	HP	
$P_{turboshaft}$	Power from the turboshaft at takeoff	HP	
P_{tot}	Power from the turbocompound at takeoff	HP	
Pme	Mean effective pressure	MPa	
T_0	Torque at max design power	Nm	
V_d	CRDID displacement	m^3	
n_{car}	Characteristic number for the 4 stroke cycle	-	2