



CONVERTIPLANE CRUISE PERFORMANCE OPTIMIZATION WITH CONTRA-ROTATING PROPELLERS

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ABSTRACT

A major problem of convertiplanes is that they need high disk-loading for efficiency in cruise and very low disk-loading for lift at vertical take-off. Contra-Rotating Propeller (CRP) seems to be a convenient solution for the tilt-rotor convertiplanes derived from the tilt-motor V22/BA609. With this propeller arrangement the rotor diameter can be significantly reduced. In this way the disk-loading for vertical take-off is the same of the traditional propeller. In the case of an aerial vehicle similar to the V22 the rotor diameter can be reduced from 11.6m down to 7m. The lower diameter and disk area significantly reduces the drag at cruise speed. In this way propulsion efficiency is increased. In the V22 case a secondary reason for using contra-rotating propellers is to increase the propeller disk-area, and achieve higher vertical lift efficiency, within a propeller diameter limited by the height of the aircraft's undercarriage. In this way the emergency "conventional" horizontal landing is possible by giving a small amount of dihedral to the wings (8 DEG). This is easy to implement due to the absence, in the contra-propeller version, of the interconnecting transmissions between the two rotors at the wingtips. Moreover, the huge gyroscopic moments of the V-22/BA609 propulsion system that induces slow response on these aerial vehicles is annulled by the contra-rotating solution. Finally, the contra rotating propellers are less subject to the roughness zone of the VRS (Vortex Ring State) as demonstrated in wind tunnel tests. The higher complication of the two contra-rotating rotors is compensated by the fact that only the blade feathering DOF is implemented in the hub. In helicopter mode, the advancing blades of each rotor operate at higher pitch angles to produce more lift without prejudice to roll trim, since the difference in lift between the advancing and retreating blades of the upper propeller are balanced by the equal and opposite lift distribution of the lower one. This concept is called the Advancing Blade Concept (ABC) and has been successfully implemented in the Sikorsky's X2 high-speed technology demonstrator. Flutter due to lack of stiffness of the contra-rotating solution have been successfully solved in the fifties (see the nearly sonic Tu95 Bear). In this paper the cruise performance of the contra rotating solution is fully analysed with Solid Woks Flow Simulation. As expected the propulsion cruise efficiency is significantly higher than the traditional propeller solution.

Keywords: convertiplane, cruise, contrarotating propellers, efficiency.

INTRODUCTION

Convertpiane is conceptually very interesting flying vehicles. 100% of power is required at vertical (VTO-Vertical Take Off) or short run (STO-Short Take Off) take-off. 15-50% power is used in cruise condition. The non-ideal off-design condition can be partially compensated by dynamic air intakes on the turboshafts. Theoretically, in a multiple engines configuration a few engines can be stopped in cruise at it was common in the WWII Gloster Meteor jet fighter. Finally, the convertiplane Lands Vertically (VL) or with a short run (SL-Short Landing). The huge amount of power installed makes these aerial vehicles anti-economical as a pure transportation or as a high lift vehicle. A good transportation aircraft will be more cost effective, while a heavy lift helicopter will move higher payloads at lower costs. The advantage of the convertiplane is that it can take the payload to helicopter sites and fly farther and in shorter time than any helicopter. Both on the civilian and military market, customers can accept the increased costs for the better performance. A major concern in this "new" type of vehicles is range. This paper is focused on a possible improvement of the maximum range on the best convertiplanes available on the market: the V22 Osprey and the BA 609. These two vehicles are conceptually very similar and a foreseen improvement is the conversion from

tilt-motor to tilt-rotor. This choice improves efficiency, range and reduces maintenance costs. In this second paper, the attention is focused on the cruise performance in terms of maximum velocity and efficiency (range). It will be demonstrated that even with extremely traditional NACA 006 unswirled blades, the contra-rotating propellers offer more efficiency with approximately half the frontal disk diameter. This concept will improve considerably the performance of the convertiplane in "aircraft mode", since the propeller wake resistance is smaller. This paper is divided into an introduction on the known improvements that can be made on the V22 design, and then the contra-rotating solution is introduced. Then cruise optimization and blade settings are discussed.

Horizontal flight

It is simpler to limit the study to three flying configurations. This approach simplifies the simulations and the certification of the vehicle by military and civil Authorities. The helicopter VTOL mode is with the rotors fully tilted upward (90 DEG). The STOL flying configuration is with rotors at an intermediate angle. The aircraft mode is with the rotors at 0 DEG. The transition between the modes is restricted to well-known conditions. The helicopter uses constant speed propeller. On the contrary, in traditional aircrafts, thrust is controlled by tip



speed and pitch. The aim is to optimize propeller and turbo shaft efficiency with thrust, velocity, altitude and temperature offset. In STOL mode, propellers polar inertia reduces aircraft manoeuvrability, control authority and controllability with relatively high thrust and low speed like in take-off and landing. In a convertiplane, this power required in helicopter and aircraft mode is larger. The Power-to-Weight ratio of a helicopter (CH47) is 0.28 while for a cargo propeller aircraft (A72) is 0.17. In a convertiplane the disk loading is always too high for the helicopter mode and too low for the aircraft mode. Since the throttling agility of propellers in aircraft mode is limited by the high propeller polar inertia, it may be convenient to have two rotational speeds for the rotors, a higher one for the helicopter mode and a lower one for the aircraft mode. In this case it is better to work with $v_{tip}=0.91$ Mach ISA-50@1000m for MTOW (Maximum Take Off Weight) STOL/VTOL take-off. In aircraft-mode cruise $v_{tip}=0.6$ Mach is used. In fact, a short noise burst at take-off is acceptable in many cases. In case of necessity, a "silent" hover/VTO can be obtained with $v_{tip}=0.7$ Mach tip speed and reduced MTOW. This solution enhances performance, while preserving operational efficiency. The turboshafts may have a "low efficiency" super-speed and an optimized "design point" lower speed for cruise. It is possible to design the air intakes for high pressures/efficiency in cruise and high-power/low-dirt in VSTO and hover. Since very large and slow moving blades limit the maximum forward speed and the efficiency, the use of contra-rotating propellers comes as a premium choice. In horizontal flight a very limited amount of power is required even at maximum speed at low altitude. In this case it is strategic to use diesel engines [1] [2] [3]. Furthermore, diesel engines have lower rotating speed than turboshaft. For this reason, the weight, design problems and reliability is largely increased [4] [5].

INTRODUCTION TO CONTRA-ROTATING PROPELLER (CRP)

The first document available of CRPs is a 1909 patent by F. W. Lanchester. The M.C. 72 set a new world speed record (over water) on 23 October 1934, for an average speed of 709 km/h (440 mph). The M.C.72 used CRP powered by a modified FIAT AS.6 supercharged V24 engine generating about 2,000 kW. The MC72 had fixed pitch CRP.

A few successful British aircrafts with variable-pitch CRP are the Avro Shackleton (1949), Supermarine Spitfire (1943) and Seafire (1944) powered by the Rolls-Royce Griffon engine, and the Fairey Gannet (1949), which used two Mamba Mk.101 turboshafts. In the Double Mamba each turboshaft drove one propeller each. Therefore, it was possible to shut down one turbine in flight, increasing endurance. In the US, the more famous CRP driven aircraft was the XF-11 that crashed in 1946 at the command of Howard Hughes.

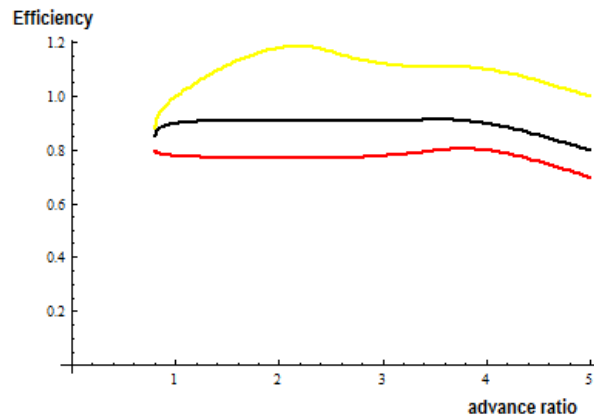


Figure-1. Off-design Efficiency of NACA four-digit CRP.

After the war Convair XFY-1 Pogo (1948) was a prime example of gearbox durability issues connected with the CRP. The flying wing bombers XB-35 and XB-42 had a CRP pusher configuration. In Russia, the Tupolev Tu-95 "Bear" (1955) is the most famous CRP driven aircraft in the world still flying. The Tu-95 has four 5.6m diameter CRPs driven by eight 11,000 kW turboshafts. It can reach 875 km/h (0.83 Mach) at cruise altitude. The civil variant of the Tu-95, a 220 passenger aircraft, still holds the world speed record for a commercial turboprop driven aircraft (Mach 0.83 at 12,000m). At high Mach numbers the propeller tips go supersonic; this fact increases the disk loading, since the supersonic part of the blade does not contribute to the thrust. The Tu-95 shows the technical feasibility of contra-rotating propellers in today's commercial market.

Kamov produced several CRP helicopters starting from the "flying motorcycle", light single-seat helicopter of Ka-8 (1947). It makes use of a CRP which dispenses with the need for a tail rotor. Almost all the Kamov helicopters feature a CRP, up the latest Ka-52 Attack-helicopter (1995). The most interesting feature of CRP is the off-design efficiency (see Figure 1).

CONTRA-ROTATING PROPELLERS DESIGN

A second contra-rotating rotor reduces the necessary disk diameter of about 40%. The polar inertia J_2 of the contra-rotating propeller will then be reduced of approximately 60%. This factor is approximately calculated by equations (1) through (6).

$$M_1 = \rho_{1L} r_1 \quad (1)$$

$$M_2 = \rho_{2L} r_2 \quad (2)$$

$$J_1 = M_1 \left(\frac{r_1}{2} \right)^2 \quad (3)$$



$$J_2 = 2M_2 \left(\frac{r_2}{2} \right)^2 \quad (4)$$

$$\frac{J_2}{J_1} = 2 \frac{\rho_{2L}}{\rho_{1L}} \left(\frac{r_2}{r_1} \right)^3 \quad (5)$$

If $\rho_{2L} = \rho_{1L}$ and $r_2 = 0.6 * r_1$ then

$$\frac{J_2}{J_1} = 0.432 \quad (6)$$

The massive reduction of the polar moment of inertia means that propeller angular speed variation is easier with contra-rotating propellers and turbine response to command (throttle authority) will be faster. The presence of the two propellers will eliminate the gyroscopic effect of propeller with beneficial effects on aircraft handling and reduced loads on tilting actuators. The transmission between the two tilting rotors at wing tips can be eliminated. In the contra rotating coaxial configuration, the possibility of splitting the power input into two paths results in a transmission design internally-balanced, compact and capable of handling greater power than many other configurations. The design is easier for multi-engine inputs with only a small mass increase per added engine. These unique features of the contra-rotating coaxial transmission have even greater importance as the input power increases as required to satisfy the need for heavy convertiplanes. The blades of coaxial-contra-rotating rotor are very stiff compared to conventional helicopter blades. High stiffness is permitted in the three principal modes of bending, the flap-wise bending, chord-wise bending and torsional bending. Only the blade feathering DOF is implemented in the hub. In helicopter mode, the advancing blades of each rotor operate at higher pitch angles to produce more lift without prejudice to roll trim, since the difference in lift between the advancing and retreating blades of the upper propeller are balanced by the equal and opposite lift distribution of the lower one. In addition, the efficiency, in terms of the maximum lift-to-drag ratio is improved. In terms of power consumption, the coaxial rotor is more efficient in hover and maneuvers than a single rotor of the same solidity and blade geometry. This concept is called the Advancing Blade Concept (ABC) and has been successfully implemented in the Sikorsky's X2 high-speed technology demonstrator. Another advantage is the reduced polar inertia. The main drawback is noise. Contra rotating propellers are noisier than single propeller even when, as in our case, the two rotors have different number of blades. The NACA 006 airfoil has been selected to reduce noise and improve VRS (Vortex Ring State) performance. In any case, contra rotating propellers allow larger vertical speeds than single disk ones. This is due to the fact that downwash velocity is higher than single rotor propellers. The hub is more complicated and heavier, but, in convertiplanes, the

absence of the interconnections between the wingtip rotors largely compensates this drawback. Finally, as we already saw in the first part, the gravity-powered autogyro mode is possible. Therefore, the convertiplane can auto rotate safely with the hubs rotated vertically and different rotational speed on the two wingtip hubs.



Figure-2. Boeing 767 showing wing-tip vortex.

CURRENT CONFIGURATION BENEFITS IN CRUISE MODE

In horizontal flight, convertiplane propellers are mounted at the tip of the wing to operate in the crossflow of the wingtip vortex (Figure-2). The propeller is aligned coaxially with the wingtip chord and is positioned in front of the engine nacelle. The engine nacelle houses an (two) ordinary aircraft engine(s), which powers the propeller. At the wing tip, the freestream velocity and the blade rotational velocity vectors add vectorially to yield a resultant velocity. A significant amount of tangential or rotational air flow is created by the spinning blades. The energy of this tangential air flow is wasted in a traditional propulsion system (Figure-3).



Figure-3. propeller tip vortices of a Grumman F6F Hellcat.

Under lifting conditions, an airfoil energises a vortex system along its span, with a concentrated vortex centred behind the wingtip (Figure-2). This vortex system is a collateral product of lift. This vortex is a major source of aircraft induced drag, which is commonly responsible for about 40% of the total aircraft drag. The wingtip



propeller rotates against the lifting vortex swirl obtaining additional thrust and simultaneously reducing the wingtip vortex. In this way it extracts energy from the vortex and converts it into propeller blade-induced thrust. Therefore, the attenuation of the wingtip vortex simultaneously increases thrust and decreases vortex induced drag. On this concept Zimmerman developed a unique design centered on a blended wing aircraft nicknamed of "Flying Pancake" (1930, Figure-4).



Figure-4. Zimmerman's flying pancake (1930).

This low drag design leads to an aircraft exhibiting shorter take-offs and landings (STOL- Short Take Off Landing). In V22/BA609 projects the careful selection of wing geometry (in particular, aspect ratio) and the wingtip propellers are an effective method to minimize induced drag and to increase effective wing aspect ratio.

Table-1. V22 VS proposed solution.

	V-22 Osprey	Proposed solution
Installed power	2 x 4586 kW	2 x 4586 kW
v- mtow	21000 kg	21000 kg
Disk diameter	11.5 m	7 m
Disk area	103.87 m ²	38.50 m ²

NEW SOLUTION: CONTRA-ROTATING PROPELLERS

Two contra rotating rotors are introduced in the proposed solution. In order to improve the autorotation performance, the NACA006 airfoil (from the Bell 212 UH-1N tip) was chosen with un-twisted blades. This choice optimizes the behavior during VRS "roughness" condition (Settling with Power). This new airfoil choice is more oriented to controllability than to efficiency (in terms of lift). Noise reduction of the contra-rotating system requires different number of blades for the front and rear rotors to reduce. In this case the front propeller has 3 blades, whereas the rear one has 4. This configuration is not the best for maximizing vertical performance: a 5front/7rear one is better for VTOL performance. The 3/5 choice is a compromise for best cruise performance and noise.

In this paper, the rotors performance is simulated with Solid-Works-Flow-Simulation. For the CFD

simulation the vehicle body and the nacelles are extremely simplified. This choice will reduce CFD accuracy but will reduce computational time by two of magnitude. In fact, the extremely efficient sparse matrix solver of Flow Simulation smoothes automatically the 3D sharp edges of the fuselage and of the nacelles. This approach reduces significantly both the mesh and solver time. For this reason comparative results are shown in this paper. The V22 wing and the blades of the contra-rotating propellers are modeled with the maximum accuracy (Figures 5 and 6). The original airfoil profiles of the V22 are approximated with the material available in literature, which is not very accurate.

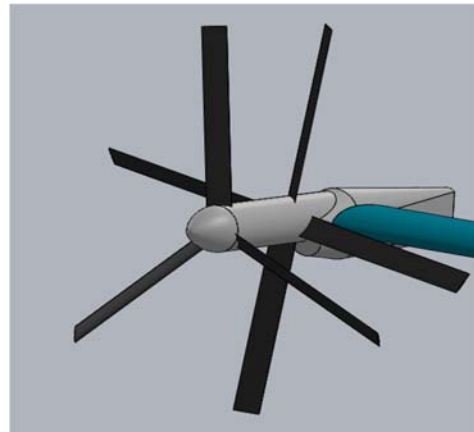


Figure-5. Simplified 3D model of contra-rotating propellers in solid works.

ORIGINAL V22 MODEL RESULTS

The results of the simulations for the original V22 configuration are depicted in figure 7. The accuracy is not optimal but the results are reasonable.

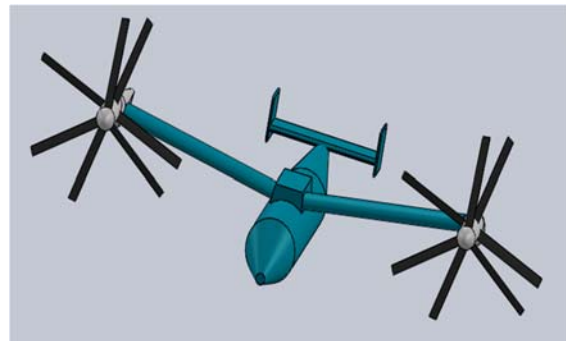


Figure-6. Simplified CAD model of the new proposal.

The best AOA (Angle Of Attack) for the rotors is 7-10 degree depending on the altitude. The second rotor has 1 degree less than the first rotor to optimize thrust and efficiency. Figure-7 shows that the new proposal produces more lift than the V22 at the same altitude and horizontal velocity.

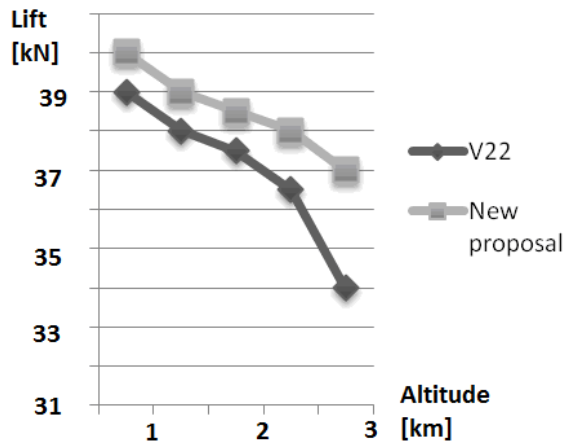


Figure-7. Lift (kN) vs altitude (km).

Figure-4 shows that new proposal with CRP produces less drag than V22 at every altitude.

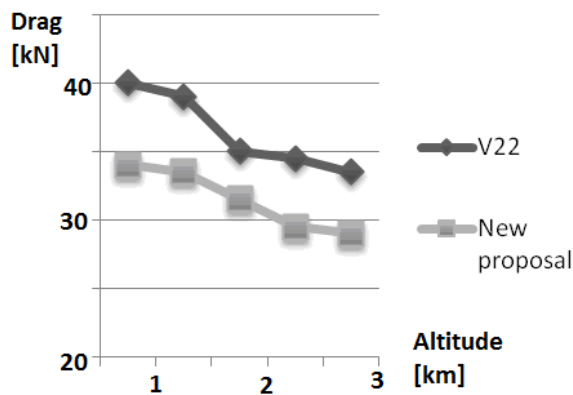


Figure-8. Drag (kN) vs Altitude (km).

The values obtained through Flow - Simulation are good as comparative numbers. More precision can be easily obtained by using mainframes instead of laptops (Figure-9).

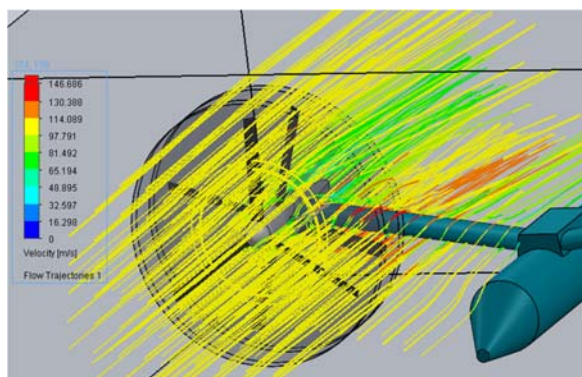


Figure-9. CFD of the new proposal (Flow Simulation).

However, this study is a good starting point. The results are completely favorable to the contra-rotating propellers. In fact, the efficiency of this new configuration is larger than the original V22 configuration. Figure-10 shows the aerodynamics efficiency of the two configurations.

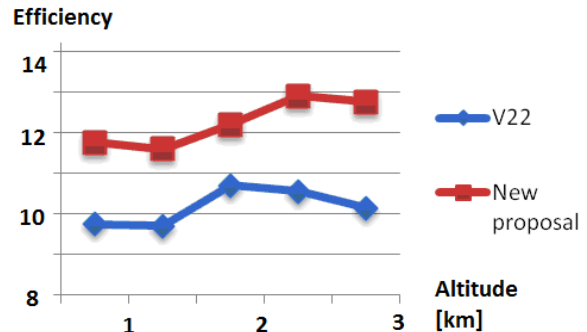


Figure-10. Aerodynamics efficiency vs. Altitude (km).

The best efficiency is 12.9 and it is reached by new proposal at about 2,000 m. The V22 reaches its max efficiency (10.7) at 1500m.

CONCLUSIONS

Contra-rotating propeller (CRP) seems to be a convenient solution for the tilt-rotor convertiplanes of the V22/BA609 type. In the case of CRP the rotor diameter can be significantly reduced. For a vehicle similar to the V22 the rotor diameter can be reduced from 11.6m down to 7m. In this paper it is demonstrated that new proposal, with contra-rotating propellers, can be a promising option for the future convertiplanes. In cruise, efficiency and lift are better than the V22 ones.

Symbols

Symbol	Description	Unit
M_1	Blade Mass Single rotor	kg
M_2	Blade Mass Single rotor of the CRP	kg
ρ_{1L}	Blade linear density Single rotor	kg/m
ρ_{2L}	Blade linear density Single rotor of the CRP	kg/m
r_1	Radius of Single rotor	m
r_2	Radius of Single rotor of the CRP	m
J_1	Polar Inertia Single rotor	kg m ²
J_2	Polar Inertia of the CRP	kg m ²



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