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STUDY AND OPTIMIZATION OF A CONTRA-ROTATING PROPELLER HUB FOR CONVERTIPLANES PART 1: VTO AND HOVERING

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ABSTRACT

Contra-rotating propeller seems to be a convenient solution for the tilt-rotor convertiplanes of the V22/BA609 type. With this propeller arrangement the rotor diameter is significantly reduced. In the case of an aerial vehicle similar to the V22 the rotor diameter can be reduced from 11.6m down to 7m. In this case the emergency 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. The V-22/BA609 configuration has a high roll polar moment of inertia with roll control implemented through differential rotor thrust. VRS is then particularly critical. The contrarotating propellers are less subject to the roughness zone of the VRS as demonstrated in wind tunnel tests. Furthermore, the airfoil chosen (NACA 0006) is particularly suited to have a smooth transition from the propeller working state to the windmill brake state. The stability of the contrarotating propellers and the possibility of the two hubs to rotate at different speed in windmill brake state, make it easier to enter into a stable autorotation state. The autogyro (autorotation) and the airplane mode landing are fundamental requirements for the certification of V22/BA609 as civilian transport. To make the certification easier it is possible to identify three flying modes for the aerial vehicle: VTOL with the hubs tilted vertically, STOL with the hubs at an intermediate angle and aircraft (horizontal hubs) for cruise. The transition can be restricted to most favorable conditions. The turboshafts may have two working conditions: in the cruise one the maximum pressure (and maximum efficiency) of the reference Brayton cycle is necessary. This pressure is achieved with the contribution of the air intake. In this mode the propeller tip speed can be near 0.5M. The lower disk diameter of the contra-rotating propeller guarantees better propulsion efficiency. The VSTOL mode is with maximum power, with lower maximum pressure in the turboshaft and with higher propeller tip speed (0.91M). The hub can be simplified with the Advancing Blade Concept (ABC) that requires only the blade feathering DOF. The upper and lower rotors require about 1 DEG of difference in AOA (Angle Of Attack) in most conditions. The gyroscopic effects are neutralized and the force necessary to tilt the rotors is much lower than the single rotor solution. This assures also better handling in most flying conditions. Finally, the two-contra-rotating-rotors-tilting mechanism is not more complicated than the single rotor one.

Keywords: convertiplane, lift, contrarotating propeller, efficiency, VRS, safety, handling.

INTRODUCTION

Convertiplanes are conceptually very interesting flying vehicles. They will take-off vertically (VTO) or with a short run (STO) with 100% of power and lift, then they will fly with 30-50% power horizontally on the wings. Finally, they will Land Vertically (VL) or on a short airstrip (SL). 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 transport payloads much more cost-effectively and faster. A heavy lift helicopter of the new generation will move higher payloads at a slower speed and on a shorter distance with lower costs. These shortcomings can be partially overcome by using modern CRDIDs (Common Rail Direct Injection Diesel) that show extremely high efficiency even in off-design conditions. For these propulsion units efficiency over 50% is common [1] [2] [3] [4] [5] [6] [7]. The advantage of the convertiplane is that it can perform operations prohibited to aircrafts and helicopters. It can take the payload exactly to destination and fly farther and in shorter time. The drawback is costs. However, both on the civilian and in the military market, costs may come second to performance. A major concern in this "new" type of vehicles is safety and certification. This paper is focused as a possible improvement of the best convertiplanes available on the market: the V22 Osprey and the BA 609. These two vehicles are conceptually very similar, with significant differences on the design choices. In this first paper, the attention is focused on the vertical lift and on the possibility to land as a traditional aircraft with the rotor fully tilted horizontally. It will be demonstrated that even with extremely traditional NACA 006 unswirled blades, the contra-rotating propellers offer more lift with approximately half the frontal disk diameter. This will improve also the performance of the convertiplane in "aircraft mode", since the propeller wake resistance is smaller. However, this subject, as the autorotation and the vortex ring state will be treated in the following papers. This paper focuses only on hover and VL. It is divided into an introduction about the known improvements that can be made on the V22 design, then the lifting propeller is introduced and the performance and optimization of the contra-rotating solution is discussed. Then a possible configuration of the new tilt rotor convertiplane is introduced and a few considerations on the implementation of this solution are discussed.

The patched prototype issue

After the Vietnam War experience, the US developed the F15 and F16 fighters. The procedure at that time was to develop a few prototypes to be tested for the final selection of the winner. These prototypes were produced with soft-tooling. On the contrary, the serial aircrafts were produced with hard-tooling. The production aircraft was then different from the prototype tested. The F15 and F16 serial production proved to be a nightmare with enormous problems to be solved in very short time during the initial production phase. By the way, this is a normal fact in the automotive field. This negative experience and the introduction of CAD/CAM with powerful simulation software, introduced the idea to produce also the prototype(s) with hard-tooling. This solution avoids the passage from soft to hard tooling. The first victim of this idea was the Space Shuttle that was born too small to be economical. In fact, the power plant had an excessive power density that required extensive maintenance and overhaul after each flight. The hard tooling approach introduced the "patched serial prototype" concept. Since the prototype is already the first production aircraft, as problems arise, patches were designed to correct problems. This approach compromises the quality and the quantity of the modifications that can be made on a new aerial vehicle. In the opinion of the Authors, an aerial vehicle that suffered from this approach is the V22 Osprey, which is a magnificent concept that was designed and patched in a very efficient way. However, the necessity to go into serial production immediately seriously limited the options available to the engineers. The result is a very good aerial vehicle that can be greatly enhanced by redesigning a few components. This paper introduces a few possible new concepts that can be introduced in the next generation convertiplane. Al Bowers, associate director of research at NASA's Dryden Flight Research Centre in Edwards, California said about the V173 Pancake STOL aircraft: "By having the propellers so very large and spinning at not-inconsiderable velocities as well, you wind up with very large gyroscopic forces. Therefore, it starts to actually behave a bit more like a helicopter, or in a modern sort of parlance, a V-22 Osprey. V-22 guys would totally relate to the way this particular aircraft operates." This means that the manoeuvrability of the V22 is limited by the gyro effects of the large propellers. Another important shortcoming of the Osprey is that it cannot autorotate and it cannot land as an aircraft with the propeller axis parallel to the ground. The rotating nacelles installation problem has already been highlighted by the possible successor of the V22, the V280, which is a tilt-rotor and not a tilt-motor. The rotating nacelles have also air intake and cooling problems, in fact horizontal (aircraft) flight and vertical (helicopter) flight have completely different aerodynamic conditions. The fixed nacelles are, within certain limits, easier to optimize for both the flight conditions.

Disc loading and hover efficiency

Disc loading $Lift_{m2}$ (N/m^2) is the propeller lift of a rotating wing aerial vehicle (e.g. a helicopter or convertiplane) divided by the rotor disc area, which the rotor(s) sweep(s). Hover (Power) efficiency P_{mass} (kW/kg) relates the mass of an aerial vehicle with the power required to keep it aloft in hover. In general, a lower disc loading yields higher hover efficiency. Therefore, the larger the area that the rotor(s) the less power is required to hover. This means that a larger rotor disc area generally means better hover efficiency. However, also tip speed is an important factor for hover efficiency. A very simplified formula to calculate the lift of a fixed or rotating wing comes from the idea of the Lift as given by the wing displacing its weight in air mass. From the length *R*, rotational speed *rpm*, angle of attack *α* and width of the wing*s*, it is possible to calculate the mass flow that the wing will displace. Similarly, to the Archimedes Principle, physical law of buoyancy, as a first approximation, it may be assumed that the aerial vehicle in hover" is acted upon by an upward, or buoyant, force the magnitude of which is equal to the weight of the fluid displaced by the body" [Wikipedia: buoyancy]. Equation (1) comes from this "theory".

$$P = \frac{rpm}{60}\pi R^2 s\rho g \sin\alpha \tag{1}$$

From (1) (2) (3) (4) (5), it is possible to obtain equation (6).

$$s = \frac{R}{\gamma} \tag{2}$$

$$rps = \frac{rpm}{60} = \frac{Vtip}{R} = \frac{\beta M}{R} \tag{3}$$

$$Lift_{m^2} v_{vertical} = rps \times s\rho g \sin\alpha \tag{4}$$

$$P_{mass} = v_{vertical} g \tag{5}$$

$$P_{mass} = \frac{g^2 M\rho\beta \sin\alpha}{Lift_{m^2}\gamma} \tag{6}$$

With equation (6) it is possible to draw the classical curves of Figure-1. The red curve is obtained with a tip velocity of 0.91 Mach (β=0.91); the black one uses a tip velocity of 0.6 Mach (β=0.6). The data used are ISA-50@1,000m, γ=100 and α=8 DEG.

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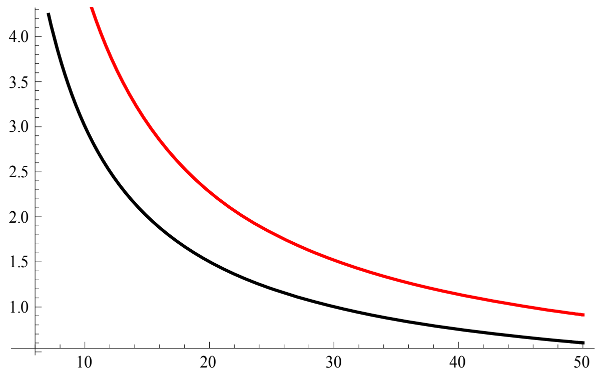

Figure-1. Disk loading [N/m^2] vs. Power efficiency [kW/kg] in hover.

It is important to evaluate the loss of Power efficiency due to reduced tip speed. Just to have an order of magnitude, Figure-2 shows the Power Efficiency loss with tip velocity from 0.91M down to 0.6M.

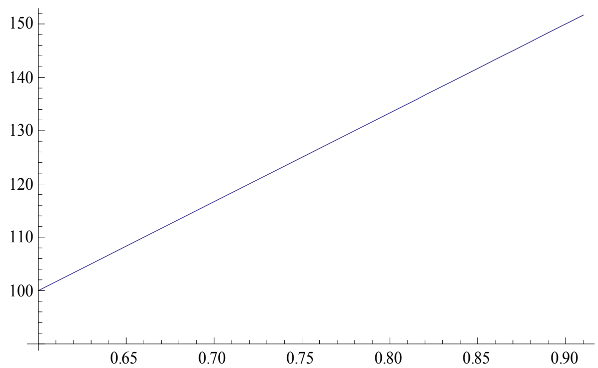

Figure-2. %Power efficiency vs. tip speed 0.6M (100%) up to tip speed 0.91M (150%); Disk loading 230 N/m^2.

The “silent propeller” of Mach 0.6 pays a huge price to the traditional one at Mach 0.91in term of power efficiency (about 50%).

Convertiplane flying modes

In order to simplify the simulations and the certification of the vehicle by military and civil Authorities, it is simpler to limit the study to three flying configurations. The first one is the helicopter mode. In this condition, the rotors are fully tilted upward (90 DEG). It is possible to take-off and land vertically (Vertical Take Off and Landing, VTOL) and to advance very slowly. The second flying condition is with rotors at an intermediate angle, optimized for STOL (Short Take Off and Landing). The third flying condition is the aircraft mode with the rotors at 0 DEG. The transition between the modes is restricted to well-known conditions. The helicopter mode requires stability with the propeller at constant speed, especially when hovering. In this case, low disk loading make the helicopter more sensitive to wind gusts. However, gyro effects tend to stabilize the vehicles with large disks (and polar inertia). On the contrary, in traditional aircrafts, thrust is controlled by tip speed and pitch. The aim is to optimize propeller and turboshaft efficiency with thrust, velocity, altitude and temperature offset. In this case, propeller polar inertia reduces aircraft maneuverability and controllability with relatively high thrust and low speed like in Take Off (TO) and landing. Another important factor is that the Power-to-Weight ratio of a helicopter (CH47) is about 0.28 while for an aircraft is (atr72) is 0.17. For a convertiplane, this difference is larger due to the "not optimized" disk loading both in helicopter and in aircraft mode. In the convertiplane, it may be easily necessary to more than halve the power setting while passing from helicopter to aircraft mode. In fact, the disk loading is always too high for the helicopter mode and too low for the aircraft mode. Since the rpm agility 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 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 hover and VTO and to cruise under v_{tip}=0.6 Mach in aircraft mode. A “silent” hover/VTO can be obtained with v_{tip}=0.6 Mach tip speed and reduced MTOW. This solution enhances performance, while preserving operational efficiency. The turboshafts may have a “low efficiency” super-speed for max MTOW and an optimized lower speed for cruise. It is possible to tailor the air intakes for high pressures/efficiency in cruise and high power in VSTO and hover. Since very large and slow moving blades limit the maximum possible forward speed, the use of contra-rotating propellers comes as a natural choice.

Contra-rotating propellers

Contra-rotating propellers have several advantages. A second contra-rotating rotor reduces the necessary disk diameter of about 40%. As speed increases the advantage in terms of efficiency increases. If the two propellers have the same polar inertia, the gyroscopic loads are balanced and the force necessary to tilt the rotor is reduced. The transmission between the two tilting hubs at wing tips can be eliminated. In the contra rotatingcoaxial 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-contrarotating rotors 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

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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. Contrarotating propellers are noisier than “single” propellers 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, contrarotating 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 will see in the next parts, the gravity-powered autogyro mode seems to be possible. Therefore, the convertiplane may autorotate safely with the hubs rotated vertically and different rotational speed on the two wingtip hubs.

Known limitations of current configuration in helicopter mode

The V22/BA609 projects are highly successfully designs that have achieved most of the required capabilities. However, as in every design, improvements can be implemented. The new requirements may start from the known limitations of the current design. The V-22 has performed an autorotation in a strict technical sense; during these tests the engine power was slowly removed to allow the aircraft to establish a stable autorotation. However, in a practical autorotation, the vehicle should be able to enter a stable autorotative (autogyro) state following an abrupt power interruption. The abrupt removal of engine power in V-22 has never been tested, since itis probable to loss the control because of the inability to maintain a safe rotational speed. The autorotation tests performed also demonstrated that the braking effect was insufficient to arrest the rate of descent. In fact, the measured final rate was more than 18 m/s. Another known problem is asymmetric VRS. The effects of VRS on the V22/BA609does not depend only on rate of descent, airspeed, and pitch attitude like in traditional helicopters, but also on roll and yaw rates. In this regard, the V-22/BA609 configuration resembles the Focke Wulf Fw 61and it is inherently different from conventional helicopters like the Sikorsky VS300 or the Piasecki HRP, because roll can change significantly the position of the wingtip rotor and the VRS parameters. Furthermore, the opposite directions of the change gives place to asymmetric VRS conditions. It is then possible for the only one of the two rotors to enter VRS "roughness" conditions with difficulties in roll control. Upon entering VRS "roughness" conditions, a conventional helicopter (like the Sikorsky VS) shudders, shakes, and becomes “sluggish” at the controls, while a V-22/BA609develops an un-commanded roll. In addition, mean-induced velocity across the rotor disk is lower in twisted blades (V22/BA609) than in untwisted ones. As descent rate increases, the twisted blade is more stable, since induced velocity distribution along the blade is more uniform. This is dueto blade twist and vortex rings. At certain descent rate, the mean induced velocity of a twisted blade is higher than that of an untwisted one. Consequently, the roughness region of VRS happens at higher descent velocity, which results in higher energy values of the phenomenon. Also the stable windmill (autorotation) state occurs at higher descent velocity for twisted blades. The V-22/BA609has a very high roll polar moment of inertia with roll control implemented through differential rotor thrust. VRS is then particularly critical. Similarly, the interception of a wake by one of the prop-rotors inducesa roll. A main safety concern is the impossibility to make an emergency landing in airplane mode, since the diameter of the rotors is 11.6m. The autogyro (autorotation) and the airplane mode landing are fundamental requirements for the certification of V22/BA609 as civilian transport.

Table-1. V22 and proposed solution.

	V-22 Osprey	**Proposed Solution**
Installed Power	2x4586 kW	2x4586 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: contrarotating propellers

In the proposed solution, two contrarotating rotors were chosen. In order to simplify the project, the NACA006 airfoil (from the Bell 212 UH-1N tip) was chosen with un-twisted blades. This choice was given by the optimum behavior of VRS "roughness" condition. In fact, this airfoil is "linear" in C_d (drag coefficient) and C_l (lift coefficient) for AOAs (Angles of Attack) from 4 up to 10 DEG. In any case the contra-rotating propellers suffer of very limited "roughness" in VRS, as demonstrated in World War II wind tunnel tests on the Typhoon fighter (R&M. No 2218 (8721) A.R.C. Tech. Rep.). The new airfoil choice is more oriented to controllability than to efficiency (in terms of lift). It was also decided the use of a different number of blades for the front and rear rotors to reduce the noise of the contra-rotating system. In our case the front propeller has 3 blades, whereas the rear one has 4. This configuration is not the best for maximizing lift: a 5front/7rear one is better. However this choice improves VRS and cruise behavior. In any case, for the autogyro mode (autorotation), the 5front/7rear solution is better, due to lower windmill speed.

In the project, the propeller lift and drag were simulated with Solid-Works-Flow-Simulation. In this study the vehicle body and the nacelles (fixed for the new proposal, tilting for the V22) have a very simplified 3D model. The V22 wing profile and the blades of the contra-

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rotating propellers are modeled with the maximum accuracy (Figures 3 and 4). The blade profile of the V22 is approximated with the material available in literature, which seems to be, in our case, not very accurate.

The reason for this choice is to enable an acceptable accuracy of the simulation focusing on the rotor blade optimization on the commercial laptop computer available. The extremely efficient sparse matrix solver of the CAE software smoothes automatically the unphysical 3D edges of the fuselage and the nacelles. This approach reduces significantly both the mesh and solver time.

Figure-3. Extremely simplified but effective new hub model.

Original V22 model results

The results of the simulations for the original V22 configuration are depicted in Figure-5. The accuracy is unknown but the lift values are reasonable.

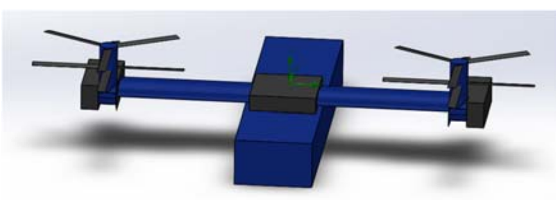

Figure-4. CFD model for the new proposal.

Figure-5 shows that the contra-rotating propeller is more effective over v_{tip}=0.8 M.

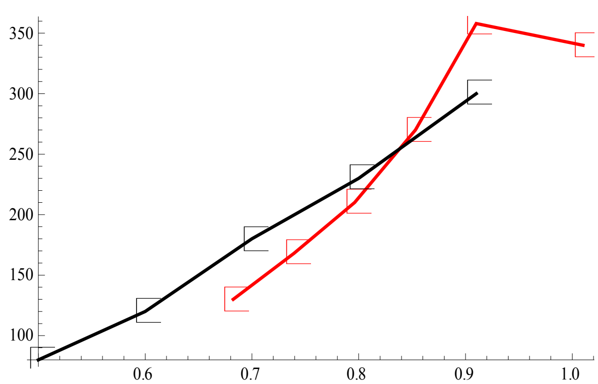

Figure-5. v_{tip}(M) vs. Lift [kN] for V22 (black) and new solution (red).

This result was obtained with AOA=8/7 DEG for the first/second rotor in hover. The supersonic tips condition was tested just to check the lift reduction. Figure 6 shows the trajectories in hover at v_{tip}=0.91M.

The values obtained through the CFD simulation cannot be taken as definitive; this is definitely a lack of precision in the results due to a number of simplifications implemented. However, the study is a good starting point for further, more detailed analysis that should be performed at least on a desktop computer. The results are favorable to the contra-rotating propeller. In fact, the thrust of this new configuration, for the same tip speed of 0.91 M, is larger than that one obtained by the original configuration of the V22.

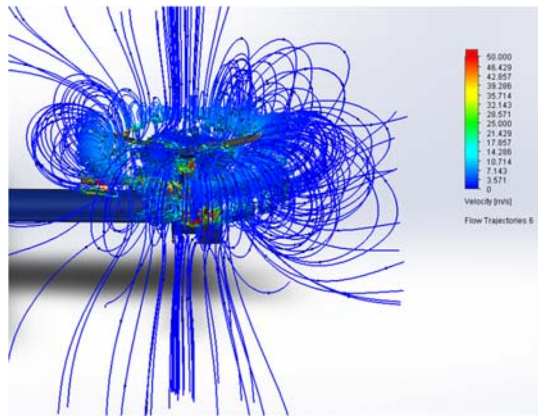

Figure-6. Flow trajectories at v_{tip}=0.91 M.

Horizontal landing

The results of the simulations for the contra-rotating solutions demonstrate that it is possible to lift the V22 even with two rotors of 7m diameter. This rotors are not the best possible in term of lift, that can be increased with more efficient airfoils and a larger number of blades. However, even in this configuration, it is possible to obtain a sufficient clearance for horizontal landing at least in emergency. In this case it is sufficient to give a little amount of dihedral to the wings (8 DEG) from the horizontal to achieve a sufficient clearance at least for emergency landing (see Figures 7 and 8).

Figure-7. Dihedral of the wings to allow horizontal landing.

Due to the type of vehicle, the horizontal landing is not common, since the STOL mode with inclined rotors is far more convenient.

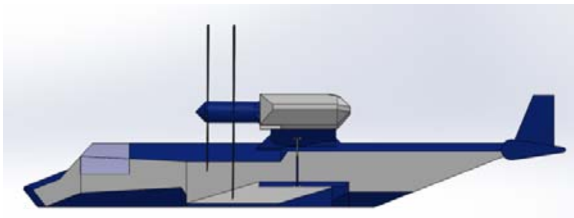

Figure-8. Propeller ground clearance with contra rotating propellers.

CONCLUSIONS

Contra-rotating propeller seems to be a convenient solution for the tilt-rotor convertiplanes of the V22/BA609 type. In this case 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 case the emergency horizontal landing is possible by giving a small amount of dihedral to the wings (8 DEG). This operation is facilitated by the absence of the interconnecting transmissions between the rotors at the wingtip. The V-22/BA609 has a very high roll polar moment of inertia with roll control implemented through differential rotor thrust (blade AOA). VRS is then particularly critical. The contrarotating propellers are less subject to the roughness zone of the VRS as demonstrated in wind tunnel tests (R&M. No 2218 (8721) A.R.C. Tech. Rep). Furthermore, the NACA 0006 airfoil has a particularly smooth transition from the propeller-working-state to the windmill-brake state. The stability of the contrarotating propellers and the possibility of the two hubs to rotate at different speed in windmill-brake-state, make it easier to enter into a stable autorotation state. The autogyro (autorotation) and the airplane mode landing are fundamental requirements for the certification of V22/BA609 as civilian transport. To make the certification easier it is possible to identify three flying modes for the aerial vehicle: VTOL with the hubs tilted vertically, STOL with the hubs at an intermediate angle and horizontal for aircraft cruise. The transition can be restricted to most favorable conditions. The turboshafts may have two working conditions: the cruise one is with the maximum efficiency and pressure of the reference Brayton cycle. This pressure is achieved by the air intake and the compressor. In this mode the propeller tip speed can be lower than 0.6M. The lower disk area of the contra-rotating propeller guarantees better propulsion efficiency. The VSTOL mode is with maximum power, with lower maximum pressure in the turboshaft and with higher propeller tip speed (0.91M). The hub can be simplified with the Advancing Blade Concept (ABC) that requires only the blade feathering DOF. The upper and lower rotors require about 1 DEG of difference in AOA in most conditions. The gyro effects are neutralized and the force necessary to tilt the rotors is much lower than the single rotor solution. This assures also better handling in most flying conditions. Finally, the tilting mechanism is not complicated by the two contra-rotating rotors.

Symbols

Symbol	Description	Unit
P	Propeller hub power	kW
rpm	Hub rpm	rpm
R	Rotor radius	m
s	Blade chord length	kg/m^3
ρ	Air density	1/s
g	Gravity acceleration	m/s^2
α	Angle of Attack	DEG
γ	R/s	-
V_{tip}	Tip blade velocity	m/s
M	Mach speed ISA-50/1000m	m/s
β	Mach number at blade tip	M
$Lift_{m2}$	Rotor disk loading	N/m^2
$v_{vertical}$	Vertical velocity	m/s
P_{mass}	Power (Hover) efficiency	kW/kg

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