ATA: THE ADVANCED TILTROTOR AIRCRAFT BY LEONARDO

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Abstract

The ATA Advanced Tiltrotor Aircraft represents a further step in the evolution of the Leonardo tiltrotor design, based on the experience maturated over more than 30 years with the study or the development of EUROFAR, ERICA, AW609, NGCTR, bringing in front of the designers the advantages, the opportunities and also the challenges of this class of rotorcraft. In this framework, the new requirements recently emerging from various potential customers has been a strong stimulus to produce a competitive and distinctive tiltrotor concept design. The approach has been to push on the advantages of this configuration, in particular increasing aerodynamic efficiency, mission performance and operational capabilities, thanks to a number of relatively simple and proven features applied in an innovative approach.

This paper describes the features of the ATA tiltrotor configuration as well as the pro's and con's of the concept, along with some results confirming the objectives of the work.

1. THE TILTROTOR TECHNICAL CHALLENGE

Although tiltrotors represent today a tiny niche of the aerospace sector, the interest for this class of aircraft is (and has been) pretty high. This could happen because the tiltrotor represents the most flexible flying machine, combining the helicopter hover with airplane-cruise flight, resulting in a helicopter able to fly as an airplane or in an airplane able to take-off as a helicopter.

Of course this flexibility has a cost, both physical and technical, the first related to the difficulty to combine hover/low speed and high speed aeromechanics, the second represented by complexity, weight and actual cost required to implement a transformation between the two regimes.

2. INTRODUCTION

While the interest in fast rotorcraft of the Leonardo former companies -like Agusta or Westland- dates back to the Sixties (ref. 15), the tiltrotors have gained more attention in the Eighties, in particular with the EUROFAR project, part of the EUREKA European research project.

EUROFAR was a joint effort by Aerospatiale, Agusta, MBB, Westland, CASA pursuing a 13 ton civil tiltrotor, with a capacity of about 20 passengers and a range up to about 700 nm. The project progressed up to a preliminary design, with most elements studied and tested to a detail level, until the interest of the participating parties decreased in the second half of the 1990s.

At the same time Agusta, the Italian Leonardo helicopter branch, started a collaboration with Bell helicopter for the joint development of the AB139 helicopter and the BA609 civil tiltrotor, the latter being initially designed by Bell and Boeing as BB609. The BA609 is a 9 passenger tiltrotor with tilting engines, pressurized fuselage and fly-by-wire controls. After the flight results but did not generate an actual prototype neither a product.

More recently, in 2013, Agusta and Westland (merged then with other aerospace companies under the Leonardo name) started the design and development of the NGCTR (Next Generation Civil Tilt-Rotor), a 8 ton tiltrotor experimental demonstrator with a new wing design, including fixed engines, split-nacelle and the so-called morphing wing for rotor download reduction. The NGCTR prototype was unveiled in 2024, starting ground tests before moving to the flight testing phase.

Figure 1 – a parallel the Leonardo company tiltrotor evolution (in clockwise order, approx. design year): EUROFAR (concept, 1990); AW609 (product, 1996); ERICA (concept, 2000); NGCTR-TD (demo, 2017)

of a first prototype in the US in 2003 and a second one in Italy in 2007, the project was renamed AW609 to reflect the acquisition by AgustaWestland/Leonardo and started a long development process, being the first product to be certified in a whole new rotorcraft category.

Shortly after, Agusta and Westland (merged into AgustaWestland) with Fokker and Eurocopter launched ERICA, a 19 seat civil tiltrotor research project aimed at the exploration of a number of critical technologies for this aircraft, including a small-diameter 4-bladed proprotor, a tilting wing section and a pass-through tilting tube directly connecting the nacelles as a single physical element. The initiative, continued in the NICETRIP research project, achieved the desired

This brief history of the Leonardo's exploration of the tiltrotor technology highlights on one hand the commitment of the Company to the fast rotorcraft product and at the same time shows how different ideas and solutions have maturated on the design tables of Leonardo. The initiatives described above moved through an evolutive line, introducing improvements and solving new challenges at every step.

A classification in the evolution of tiltrotors could be useful to follow the various steps in this technology and is introduced here. In fact, although the actual applications are limited to a few hundreds of V-22 models, the history of tiltrotors has followed a series of steps, similarly -for example- to the well-known classification of fighter jets [14].

The 1st tiltrotor evolution consists of the pioneers, dating back to the Fifties, namely the Transcendental P1 or the more successful XV-3, both demo aircraft. The introduction of the turboshaft characterized the 2nd evolutive step, with the XV-15 tested in flight and other machines stopped at design stage. The 3rd evolution is adding fly-by-wire controls, offering easier piloting, higher payload and enabling actual products, such as the V-22 or the AW609. The 4th evolution seems to be well represented by the Bell V-280/MV-75 and the Leonardo NGCTR, characterized by non-tilting engines, i.e. normal turboshafts, with clear economy and operative advantages. What could be the next evolutive step? For sure a new class of tiltrotors will benefit of more experience from the field and will face more stringent challenges: in several aspects the Leonardo Advanced Tiltrotor Aircraft is aimed at introducing important improvements, so it could be a good representative of this new evolution.

3. THE IMPROVEMENT AREAS FOR TILTROTORS

The ATA Advanced Tiltrotor Aircraft represents a further step in the history of the Leonardo tiltrotor design,

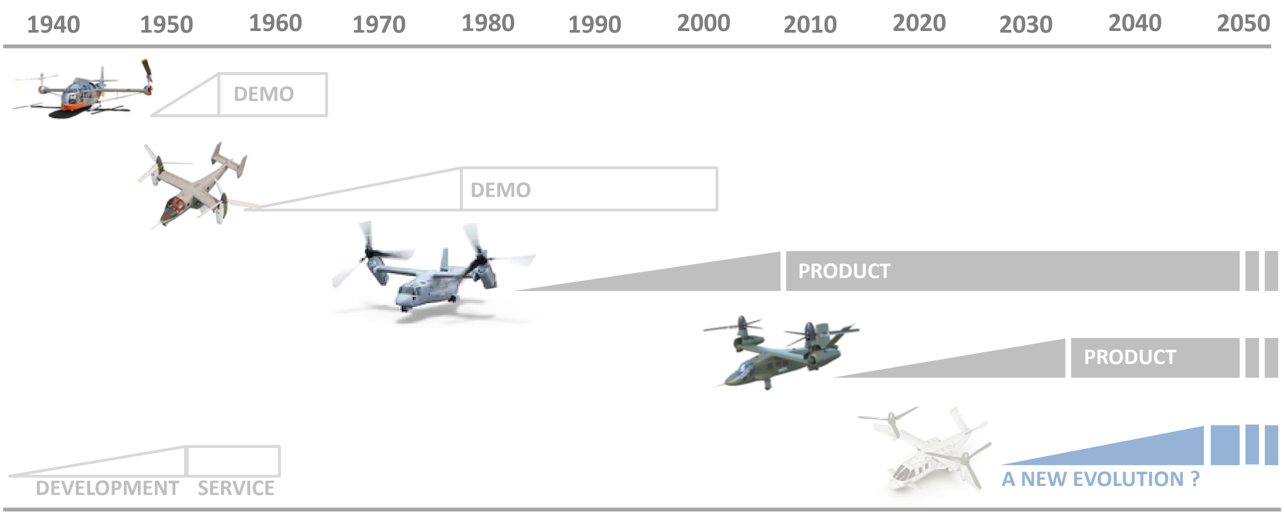

Figure 2 – a chronological representation of the tiltrotor evolutions

based on the experience matured over 40 years of studies and tests, which brought in front of the designers the advantages, the opportunities but also the challenges of this class of rotorcraft.

Of course, Leonardo (and formerly Agusta and Westland) has not been the pioneer of the tiltrotor configuration, which essentially has been historically pursued by Bell Helicopter, with many prototypes built (XV-15, TR901, V280) and one monumental product (V-22) put in service. However this second-best position has offered for a few years an unbiased point of view to the Leonardo engineers, with the opportunity to learn from successes and failures without the constraints of a product-driven unique path. And some original design results reflect this freedom in the interpretation of the tiltrotor configuration: the ERICA solution, with small rotors, has shown the possibilities of an airplane-mode take-off and landing, so the NGCTR morphing wing has explored an innovative solution to the wing download issue.

This has provided Leonardo with some cards to play on a variety of scenarios for tiltrotors, including civil and military, thanks to a good sensitivity of the effect design solutions, which in turn can be put in place depending on the specific requirements or market needs. On the other hand, this needs to consider the design cost of a transformative machine, which is essentially the weight (and the cost) associated to the transformation function, which in the case of the tiltrotor is the tilting system. This design cost is somehow fixed, so once paid it does not increase if other features or performances increase. In other words, once the design has taken into account the weight/cost of being a tiltrotor, all features can be improved almost at no additional cost. For example, if the market is stressing the hover performance, then engine, transmission, rotors can grow as necessary, but the tilting system does not. Same thing if the requirement asks for range or for speed.

With a clear mapping of product needs versus design features and cost, the designers can work towards

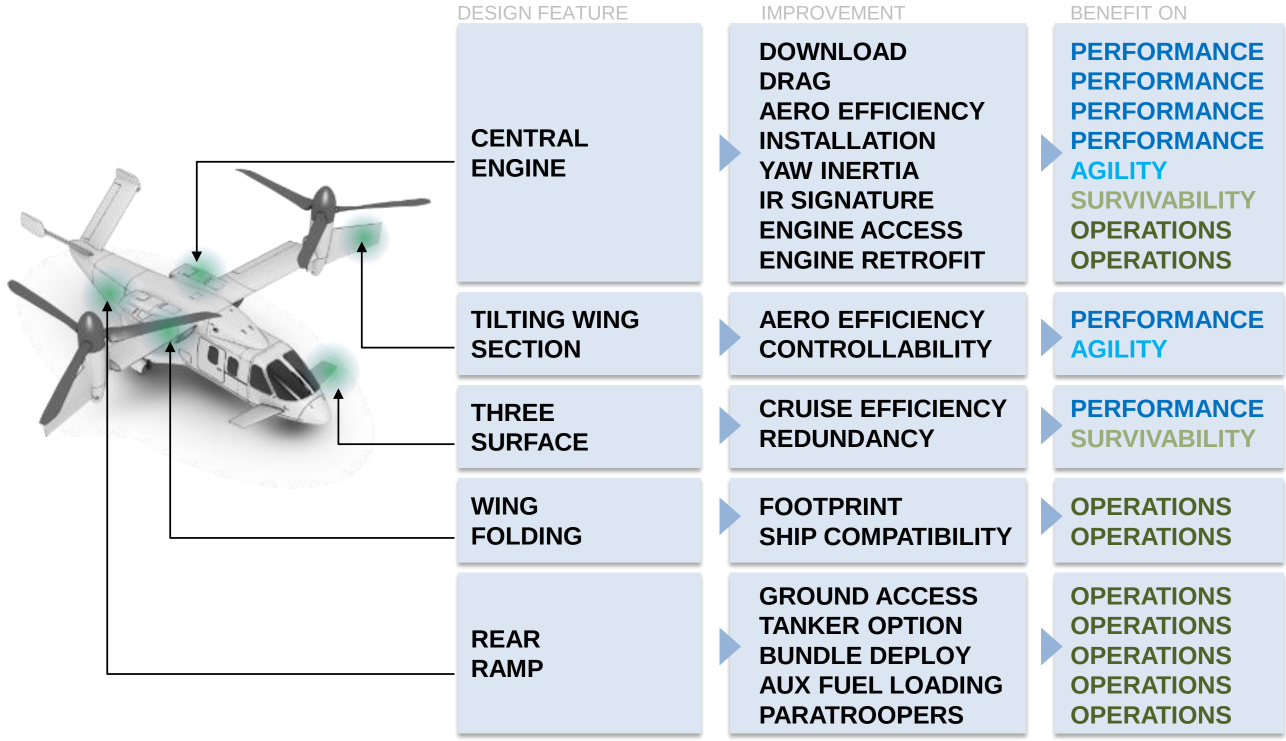

Figure 3 – A simplified mapping of the libk between design features and benefits of the ATA tiltrotor concept

specific targets in their area of responsibility, building up an overall solution compliant as possible with the requirements, assessing the feasibility or highlighting the gaps and shortfalls.

In this framework, the new requirements recently emerging from various potential customers have pushed on range rather than just speed, driving the possible design towards efficiency and cruise performance. Also important for the design are some other recent operative needs, such as cabin access, aircraft footprint, interoperability and maneuverability. This shaped the need/features map for the ATA, centered on the following improvement goals.

- Range: directly linked to cruise performance in terms of required power and fuel consumption, and indirectly linked to hover performance and empty weight because of the available fuel to be used in cruise. The design features involved are therefore drag, weight, download, engine performance and efficiency, so strongly impacting on aircraft configuration and size.

- Speed: directly linked to cruise performance in terms of available and required power, therefore related to engine performance and drag, so strongly driving the aircraft configuration and size.

- Agility: directly linked to control power, aircraft inertia engine efficiency. While this can clearly drive a dedicated design, achieving agility in presence of other needs, such as mission performance, payload etc., could be problematic and a compromise will be necessary.

- Survivability: linked to aircraft performance and to various attributes such as detectability, maneuverability, vulnerability which can strongly determine the whole aircraft design and configuration; this need can completely drive the design but in presence of other requirements, compromise will be necessary.

- Operativity: this can be related to various aircraft attributes, ranging from overall characteristics (footprint, weight) to specific details (cabin access, load handling, maintenance accessibility). This aspect needs to be considered throughout the design, seeking win-win solutions where operativity and other goals are achieved at the same time.

4. THE ATA CONCEPT FEATURES

One simple but effective way to look at the tiltrotor pros and cons could be to represent them as:

tiltrotor value = (benefit) / (design cost) where the benefits are proportional to the achieved performance, while the costs could be regarded as a fixed cost, i.e. a penalty paid for the transformative configuration irrespective of the benefits.

The approach of the overall ATA design has been therefore to push on the tiltrotor advantages, in particular increasing aerodynamic efficiency, mission performance and operational capabilities, thanks to a number of relatively simple and proven features applied in an innovative approach.

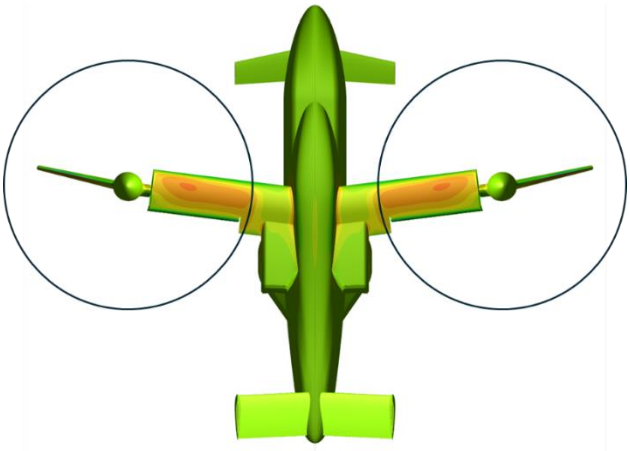

Figure 4 – top view of the pressure distribution in hover conditions on the ATA, where download advantage is clearly highlighted

The ATA design features a central powerplant —two engines positioned near the fuselage— differing from traditional tiltrotors like the V-22 and AW609 which rely on a tilting nacelle architecture. These early tiltrotors derived their design from the XV-15. The ATA incorporates a full-span interconnect driveshaft for power management in case of engine failure. This central powerplant concept has been explored and utilized in other tiltrotors, including the XV-3, the Bell Pointer and Eagle-eye (unmanned), as well as the in the Bell V-247 concept. They all employed a fuselage-mounted engine powering the rotors via shafts.

The key advantages of the ATA configuration, mostly related to the central powerplant design, consist of:

- **Drag Reduction**: The streamlined fuselage installation reduces drag, contributing to overall aircraft efficiency. (drag is reduced by more than 15% compared to conventional tiltrotors)
- **Download Reduction**: By positioning the engines on the fuselage, the 'download' – the apparent increased weight load on the rotors due to downwash – is minimized (potentially by over 3% of aircraft weight), compared to nacelle architecture that maintain a non-tiltable engine exposed to the proprotor downwash.
- **Wing Configuration**: This design allows for a non-tilting engine configuration, eliminating the need for complex shaft designs and promoting efficient airflow.
- **Tilting Wing Sections**: The central powerplant design enables the integration of a large tilting wing section extending beyond the nacelles, leading to a significant increase in maximum cruise efficiency with a net increase in lift-to-drag ratio (L/D) up to 12-13 compared to 9-10 of conventional tiltrotors.
- **Engine Intake Optimization**: The central powerplant location ensures cleaner airflow into the engines, reducing losses, especially during hover, compared to traditional tiltrotor configurations where rotor downwash can significantly disrupt airflow.
- **Engine Flexibility**: Allows selection from a wider range of engine models, without being restricted to a limited selection suitable for tilting operations. This represents an important degree of freedom during the design phase as well as an industrial advantage for possible cost efficiency and an operational advantage if common engines can be used.
- **Engine upgrade possibility**: the de-coupling of the engine (and its mass) from the wing allows a large freedom in modifications or retrofit of the engine itself, because a change of this element wouldn't in any case alter the wing dynamics.
- **Engine Maintenance Access**: Simplifies maintenance procedures due to easier engine access, avoiding for example the need to conduct maintenance operations on a large footprint.
- **Survivability**: Offers potential for intrinsic shielding the engines from external threats, helping survivability by minimizing both detectability and vulnerability.
- **Debris Protection**: The wing-root engines location offer natural protection against debris during ground operations, which is particularly relevant when operating on rural infrastructure or unprepared terrain.

• **Agility**: The central engine location strongly reduces the aircraft inertia in roll and yaw, enabling -for the same control power- higher accelerations around these axes, with direct improvement on some of the fundamental elements in the aircraft agility.

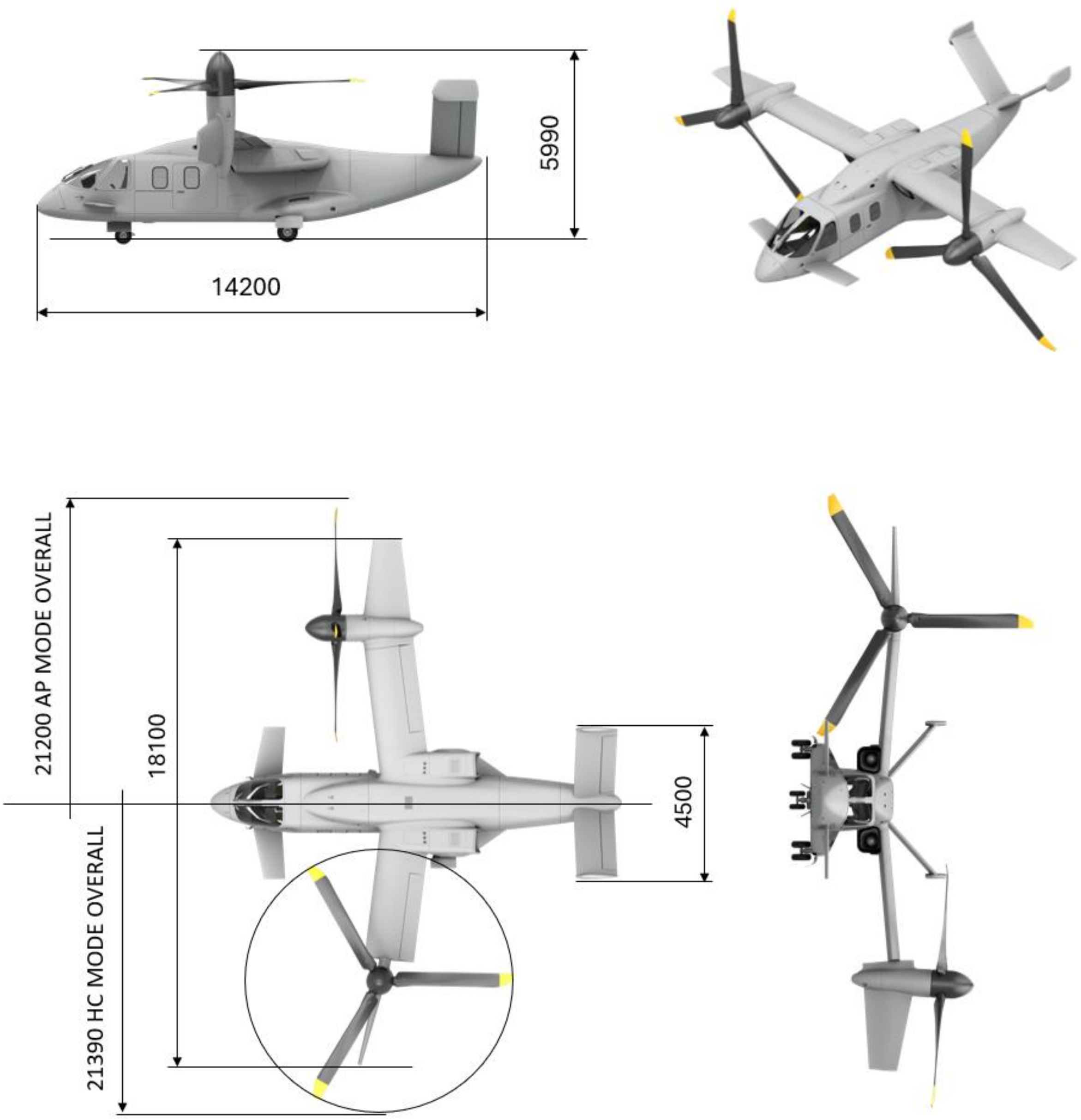

Figure 5: views of a possible ATA concept application, with dimensions in mm. The picture highlights the ERICA and NGCTR heritage, respectively in the tiltable wing section (ref. 9) and the V-tail with the aerodynamic tip devices (ref. 8, 10).

Other possible features enabled by the ATA configuration include a rear ramp for optimal access, a canard surface for trim optimization and a foldable wing for reduced hangar footprint.

5. THE ATA LAYOUT AND ARCHITECTURE

The Advanced Tiltrotor Aircraft (ATA) is a twin-engine tiltrotor aircraft featuring two side-by-side rotors, central fuselage and powerplant installation, a high wing, a V-shaped tail and a forward aerodynamic surface. The concept is of course scalable to different ranges: a generic utility/cargo application in the 10..15 ton size is used as a reference for this article.

The ATA fuselage is not pressurized and can be divided in three main parts: the forward fuselage, with the cockpit able to accommodate two pilots, the central fuselage, able to accommodate the payload or the passengers (with pax seats in the main cabin plus optional seats in the rear ramp area), rear fuselage, able to accommodate a rear ramp to ease passenger and cargo access. The forward fuselage is also provided by large windows to guarantee pilots correct external visibility, while central fuselage can be equipped with side sliding doors and windows. The cabin is accessed either by the rear ramp or by lateral doors. Emergency exits, provided on both aircraft sides, can be considered in general all windows and the lateral access doors. Additional emergency exits can be also equipped in the rear ramp area. The Landing gear is retractable, with conventional front tricycle wheeled configuration: the nose landing gear retracts into the forward fuselage, the main landing gears retract into two lateral external sponsons.

The Wing is characterized by slight forward sweep angle / dihedral angle and can be divided in three main parts: central section attached to the fuselage *upper deck, intermediate sections with flaperons, out*board tilting sections including the nacelles. Rotors are installed on streamlined nacelles fitted to the tilting wing sections, which extend outboard of the nacelles; the tilting wing can rotate from vertical to horizontal position enabling aircraft to operate respectively in helicopter and airplane mode. The tail, connected to rear fuselage, is V-shaped and equipped with control surfaces and aerodynamic tip winglets. An optional forward aerodynamic surface, or canard, is connected to the aircraft nose and can be possibly fixed, all-movable or equipped with a trim surface.

The engines are installed in the wing-root area, structurally attached to the upper central fuselage, with air provided by forward-facing air intakes, while the exhausts are directed rearward, aside the rear fuselage. The drive system is connecting the central powerplant installation with the wing nacelles and is mainly composed by a first reduction gearbox directly connected to the engine outputs, a second reduction stage driving the interconnecting shaft, an interconnecting shaft passing through the central wing sections to the nacelles, a third reduction stage into the tilting nacelles coupled to a reduction stage, connected with the rotor hubs. An accessory gearbox can be installed on the interconnecting shaft central section to feed power to auxiliary equipment. An Auxiliary Power Unit can be positioned on the fuselage upper deck in front of wing central section, connected to the auxiliary gearbox.

The fuel is contained into several self-sealing bladder fuel cells: main tanks are located under the central fuselage floor and in two lateral rear bay tanks, positioned beside the rear ramp along the fuselage sidewall, furthermore an engine feed tank is positioned on upper deck between the wing root backside and the two engines.

6. THE ATA OVERALL SIZING

The rotorcraft sizing is typically based on mission requirements and spot performances needs, from hovering conditions up to high-speed ones; each VTOL architecture has specific peculiarities but, when the target range is above ~600 nautical miles and the required speed is above ~220kts, the tiltrotor is the most efficient VTOL solution, as can be briefly resumed from the picture below, where conventional helicopter and tiltrotor main features are compared one each other.

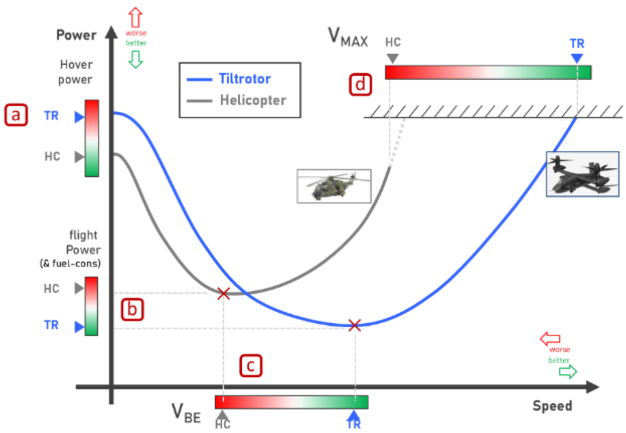

Figure 6: illustrative chart of power required vs speed, comparing helicopters (in grey) and tiltrotors (in blue).

As reported in a notional power required versus speed chart (Figure 6), helicopters have higher hovering capabilities than tiltrotors but are not capable of reaching best cruise speed with low power consumption (and, consequently, have limited range capacity). Moreover, helicopters are limited in maximum speed because of physics, not impacting tiltrotor when in wing-borne condition. In order to obtain a tiltrotor sizing that is not only able to reach high speed, but is also highly efficient (and so efficiently scalable when a long-range mission is the target) an optimal solution needs to be figured out, acting on the compactness of the design and on the power consumption balancing, harmonizing hovering and high speed conditions; to do this, rotor and wing need to be accurately sized to optimize their specific design points, as illustrated in the figure below. For hovering, rotor sizing is a compromise between compactness and performance, with optimization achievable through dedicated wing features, aimed at improving aerodynamic download; for high speed the efficiency can be improved thanks to the optimization of the fuselage drag, together with increased wing aspect ratio. Finding the correct power balancing between the two typical conditions is a challenging task and the ATA design features can be combined to produce the optimal compromise, as illustrated by the picture below.

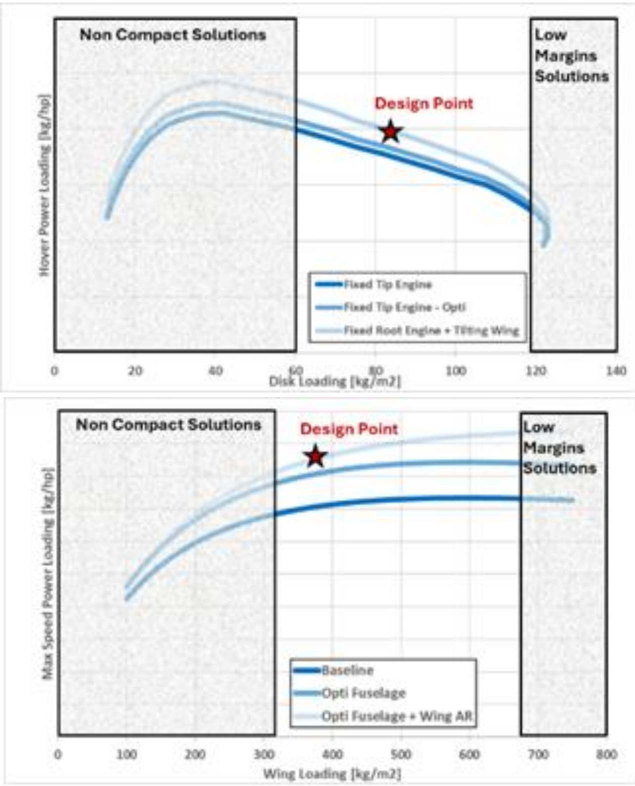

Figure 7: example of power loading vs rotor and wing design attributes

Such balanced sizing between rotor and wing, together with other ATA design features, enables solutions with high specific range, far above conventional solutions, taking advantage not only from airborne operations at high speed, but also optimized power consumption; the trend for the ATA solution, at mission target speed, is reported below.

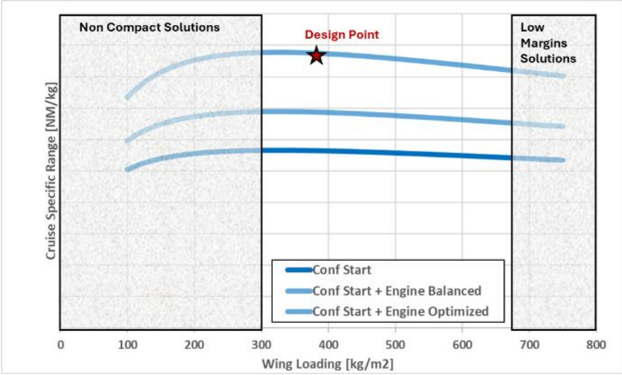

Figure 8: example of cruise efficiency vs wing design attribute

7. THE ATA AERODYNAMICS

The aerodynamic configuration of the ATA tiltrotor was designed to maximize cruise efficiency within the typical constraints of a tiltrotor architecture, specifically considering nacelle tilting, compact footprint, adequate stall velocity for smooth conversion and a large rotor diameter for efficient hover and minimal wing loading. To achieve high efficiency and low wing loading, it’s crucial to maintain the inboard wing surface area as small as possible by adjusting the wing chord. Once the minimum inboard wing area is defined, where the span is dictated by the rotor radius to maintain a compact and lightweight ATA tiltrotor, the wing chord is minimized while adhering to aeroelastic and structural thickness constraints. Verification of the minimum wing incidence (Vmin) with the conversion corridor and flight envelope at altitude is essential. Selecting a small inboard wing, despite the use of flaps and vortex generators, requires additional wing area.

A solution to increase the wing surface without increasing hover wing download (due to rotor wake) is the adoption of an outer tilting wing section, integrating the tip section of the wing and an additional section outboard of the nacelle to provide the necessary lift coefficient for the target Vmin. This feature not only maintains low wing loading but also increases the total wing aspect ratio when there is a continuous geometric relationship between the inboard wing, nacelle, and outboard wing section. The presence of a tilting wing section derives from the innovations studied in the ERICA tiltrotor within the NICETRIP program, where such element was enabling sufficient lift area for flight in airplane mode while minimizing hover wing loading – a primary aerodynamic trade-off for the tiltrotor configuration.

Regarding the inboard airfoil design, it was found that the introduction of the maximum allowable aerodynamic thickness – 23% – minimized premature divergence or stall onset keeping at the same time the smallest possible chord length, with benefit on download and cruise efficiency. If instead a lower thickness airfoil had been selected, a reduction in CD0 would be achievable, at the consequence of an increased wing chord. However, the reduction in CD0 in terms of overall tiltrotor performance did not fully offset the increased wing loading caused by the larger chord. Increasing the surface area of the external tiltwing – where profiles can be thinner – is a more effective solution than expanding the inboard wing surface area, as these profiles do not need to structurally support the bending moment generated by the rotors during helicopter mode.

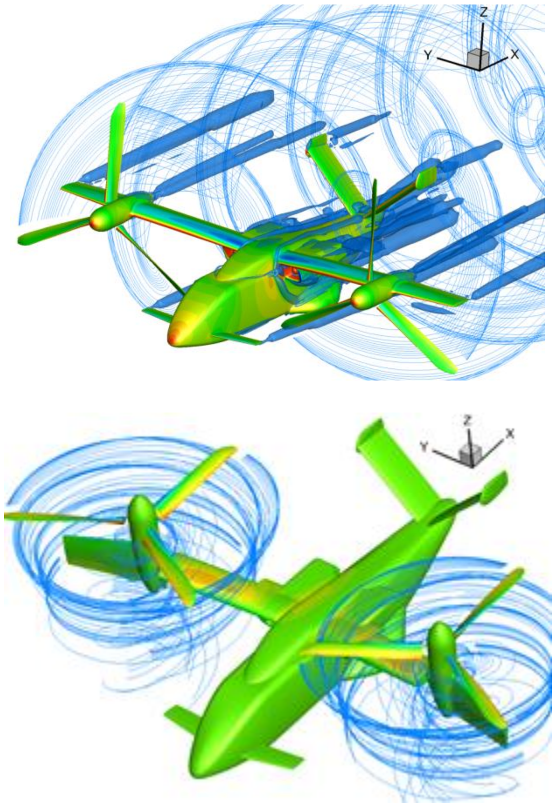

Figure 9: CFD analysis of ATA tiltrotor in Cruise and Hover with rotor effects

All those aerodynamics trade-off and benefit have been demonstrated by using interactional CFD simulations previously validated [7] on other tiltrotor programs against experimental results, Figure 9.

The presence of the outer tiltwing design in the ATA configuration has been found very effective in maximizing cruise efficiency and reducing download for the same best range speed and minimum speed requirements. The drawback of this feature are mainly the increase aerodynamic loads in VTOL mode conditions, although thanks to heavy 3D effects at nacelle angle >=50 they have been found not so impactful on the aircraft weight, Figure 10.

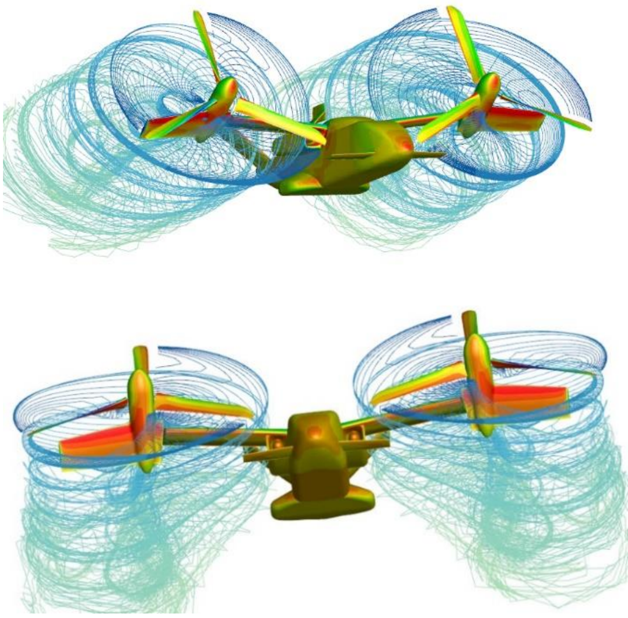

Figure 10. CFD analysis of ATA tiltrotor in Conversion mode with rotor effects.

The ATA tiltrotor configuration, as an investigational option, includes the possibility of incorporating a third aerodynamic surface – a Canard – with two operational functions: the ability to carry suspended loads and the minimization of trim drag at cruise. Concerning aerodynamic efficiency, a Canard with a lower aspect ratio and airfoil thickness compared to the main wing can be beneficial. Like the external tiltwing, it allows unloading the required lift area without increasing hover wing loading. However, if a high aspect ratio design is not feasible due to architectural or structural limitations, introducing a Canard can be effective in minimizing trim drag, not just at a single point during cruise, but across the entire flight envelope if the center of gravity excursion is significant, and the surface possesses a trim control capability with a small trailing edge flap.

Another distinctive Aerodynamic feature is the introduction of tip design on the vee-tail, “finelts”, allowing to match the bare aircraft stability required derivatives keeping the tail compact adding up to 10% increase in effective tail volume and without the need to modify the key parameter, dihedral angle, along the design process if the requirements change within a 10% variation. These devices must be both aerodynamically effective and easily integrated to mitigate challenges associated with maintaining a consistent vee-tail geometry.

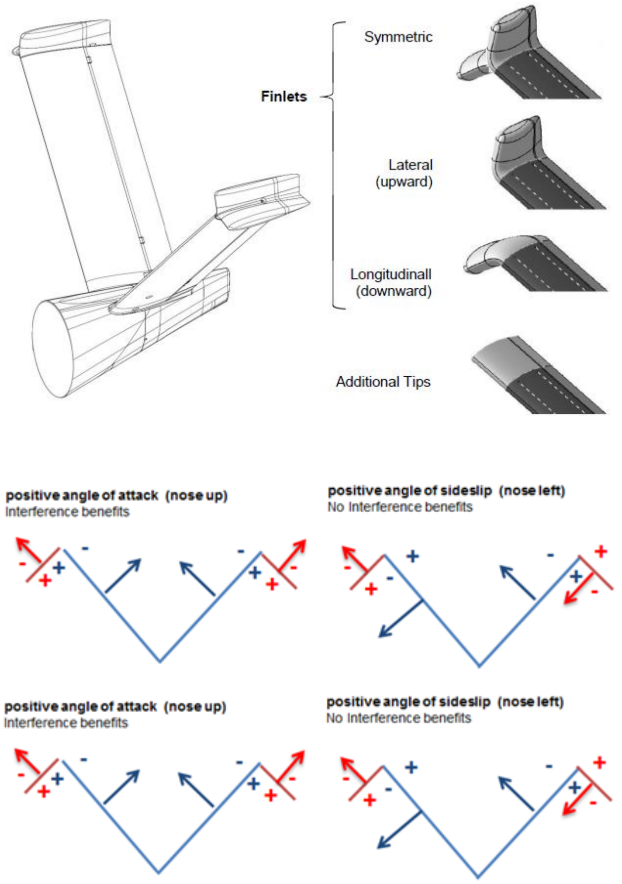

Figure 11. Finlets basic principles Aerodynamics function

As detailed in Reference [7], strategically positioned finlets can selectively influence stability characteristics while preserving the integrity of the overall vee-tail geometry. This approach allows for independent adjustments of longitudinal and lateral-directional stability.

For instance, downward-oriented finlets were found to increase longitudinal force characteristics when subjected to a positive angle of attack. Conversely, adjustments to angle of sideslip produced a negligible increase in lateral force – a result of the increased wetted surface not proportionally translating to an amplified aerodynamic force due to fin interference. Conversely, upward-oriented finlets demonstrated an ability to enhance lateral force with angle of sideslip, while offering limited impact on longitudinal force. These findings were validated through preliminary CFD and wind tunnel testing, reinforcing the ability of finlet configurations to tune stability characteristics in one axis while maintaining the other, Figure 11.

8. THE ATA FLIGHT CONTROLS

The ATA Flight Control design laid their foundation on proprotors and airplane primary control allocation strategies mostly inherited from experience matured in the perimeter of AW609 and NGCTR-TD programs, Figure 12. The gearing control laws, i.e. mapping longitudinal, lateral, directional and thrust axis commands into individual aircraft controls, provides a transparent control phasing with nacelle angle (aircraft configuration) and flight condition (airspeed, pressure altitude, etc). Control allocation logics essentially prescribe how the aircraft flight effectors redundancy is exploited to achieve desired control characteristics.

Swashplate controls encompass collective, longitudinal cyclic and lateral cyclic actuators. Symmetric Collective Pitch control (SCP) is used for thrust control laws and beta governing function (rotors RPM regulation), whereas Differential Collective Pitch is exploited for lateral and directional axis controllability depending on aircraft configuration. Symmetric usage of longitudinal cyclic actuation (Symmetric Longitudinal Pitch) is exploited to control longitudinal axis in VTOL Helicopter and Conversion modes, whereas it offers a suitable load reduction device (blow-back compensator) in Airplane mode when the longitudinal axis control is transferred to V-Tail surfaces. Differential Longitudinal Pitch command path is used to handle aircraft controllability about directional and roll axis depending on aircraft configuration. Based on NGCTR-TD design experience and well established Bell-Boeing Osprey flight controls design characteristics (Ref. 11, 12), ATA lateral cyclic actuation enables two functional features: (1) Improved lateral controllability in low speed VTOL Helicopter mode (e.g. bank attitude adjusted independently from lateral speed) via symmetric mixing (Symmetric Lateral Pitch) and (2) rotors trim adjustment (to minimize steady flapping) throughout the whole flight envelope and lateral-directional stability augmentation in high speed conditions via Differential Lateral Pitch command (i.e. inboard and outboard rotors' tilt).

Airplane controls comprise inner wing flaperons, which provide aileron function through differential command, and V-Tail control surfaces. These enable both elevator and rudder control functions by properly mixing symmetric and differential inputs to left and right ruddervators, similarly to LHD NGCTR-TD aircraft. In Airplane mode, the directional control authority is shared between proprotors' DCP and V-Tail rudder function, based on a functional allocation principle. When both equivalent control surfaces are available, the DCP is responsible for aircraft directional trim (mast torque balancing) and compensation of adverse yaw due to rotors in turn maneuvers. On the other hand, rudder oversees providing higher frequency stabilization of lateral-directional dynamics (yaw damper function), besides the compensation of possibly provers yawing aerodynamic effects associated to full-span flaperons. Directional trim function is not allocated due V-Tail in order to ensure the maximum authority available for elevator function, although a suitable prioritization logic is capable to allocate part of rudder control authority to DCP command path should insufficient residual control authority is available to rudder in a given condition. Additionally, the earlier described optional canard surface can be designed according to either secondary or primary control requirements. In the former case, the actuation requirements would be less demanding (both in terms of performance and reliability) and the resulting canard surface could be used as an effective trim device, through trim laws scheduled in the Control Laws Software, to improve aircraft cruise performance or to possibly extend CG excursion - similarly to a commercial airplane variable adjustment stabilizer. Conversely, in the latter case, the canard could provide: (a) a reliable redundant effector to longitudinal axis in Airplane mode, should a major damage (e.g. a ballistic one) affect the V-Tail. Similarly, it should be noted

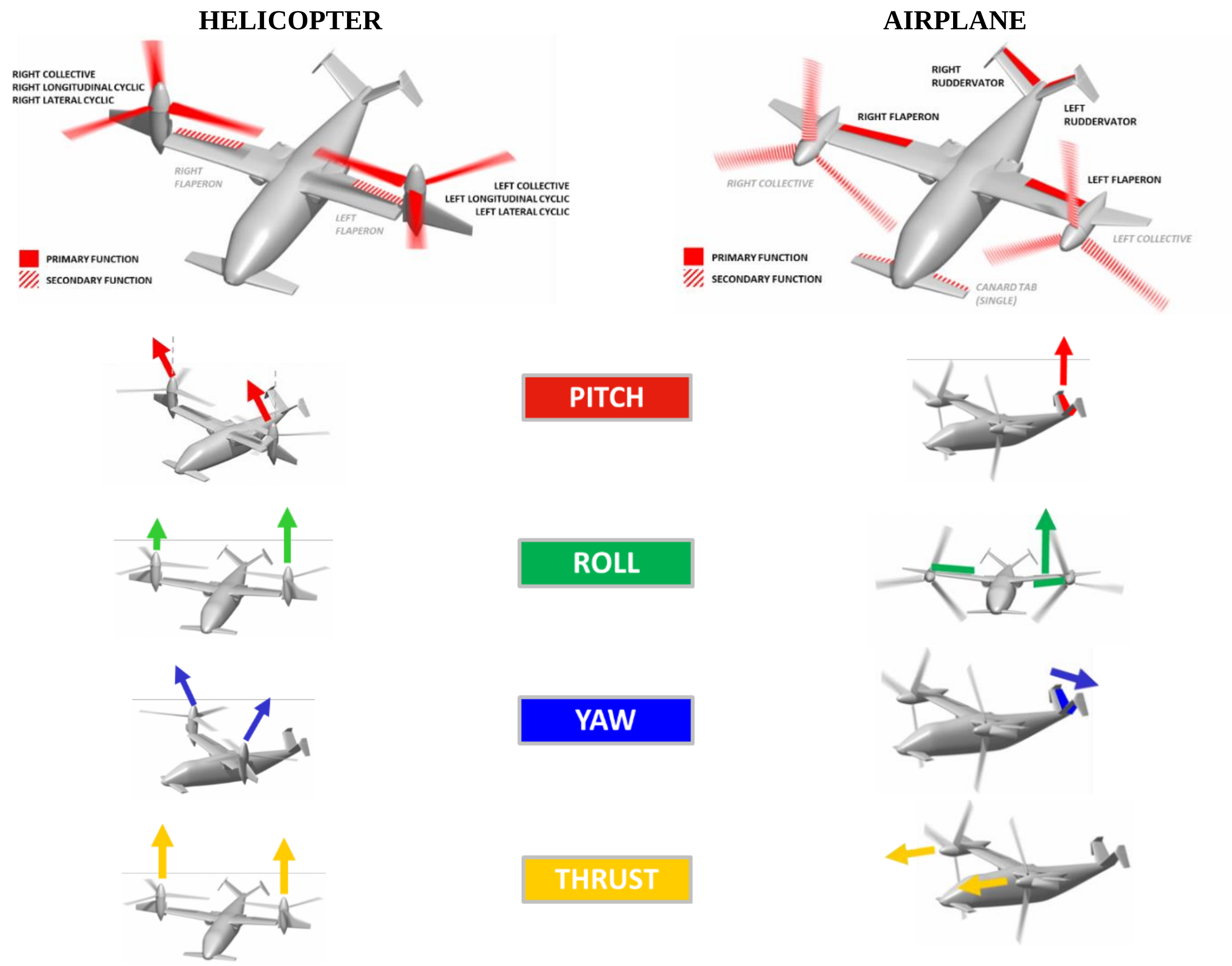

Figure 12. ATA flight controls allocation in Helicopter and Airplane mode.

that the directional functions attributed to rudder can be totally allocated to rotors' DCP (as for LHD AW609 design) if V-Tail control surfaces cannot be operated. These innovative features would improve the aircraft survivability characteristics. (b) A powerful aid to achieve desired dynamic stability characteristics about pitch axis, e.g. to relax aircraft static stability due to V-Tail, and (c) Active controlled canard can ensure a very effective assisted power-off descent by ensuring that the aircraft pitch attitude is correctly set during windmilling gliding (efficient negative lift producer at minimum drag), emergency reconversion and VTOL autorotation phases, thus avoiding dangerous rotors' speed droops (e.g. due to rotors edge-on flow conditions) or aircraft overspeed conditions.

ATA configuration controls include auto-flap function, which exploit the inner wing flaperons displaced symmetrically, and the outer wing surfaces, which are symmetrically tilted together with the nacelles throughout the Conversion corridor. Conversion actuators are properly sized to provide the reliability and performance required to complement, in VTOL mode, the swashplate primary control actuation. Specifically, the ATA flight control laws implement an Active Mast Tilt function which processes suitable symmetric and differential mast tilt commands in order to improve the longitudinal, lateral and directional control power whilst alleviating the proprotor's disc flapping. The ATA split gearbox architecture minimizes the inertial load associated to fast conversion and reconversion transients. Also, the reduced roll and yaw inertia associated to ATA mass configuration and the innovative control features of AMT function enable optimal aircraft agility and handling characteristics.

9. THE ATA DYNAMICS

The aeroelastic stability of the tiltrotor combines all the aeroelastic phenomena of both fixed wing aircraft and rotary wing aircraft and, in addition, it has its own specific phenomena, e.g. prop-rotor whirl flutter.

The phenomena typically include Global Instabilities (Classical fixed wing flutter, Prop Whirl Instabilities, Ground Resonance, On-ground instabilities), Isolated rotor instabilities (Blade flutter, Pitch-lag, Pitch-flap instabilities), Control Surfaces Stability (Vertical Tail, Horizontal Tail, Elevator & Flaperon with Control System), Drive Train Stability.

The aeroelastic phenomena are discussed below, especially highlighting the implications more specific of the ATA tiltrotor configuration.

The classical fixed wing flutter, which is not specific of the ATA tiltrotor, is caused by the aerodynamic coupling of the bending and the torsion modes of the fixed surface: if the wing torsion motion leads bending motion, then the unsteady airloads can create positive net work on each cycle and cause the instability.

The proprotor whirl flutter is due to the coupling of the fundamental rotor modes (Cone, Cyclic Flap & Cyclic Lag Modes) with wing flap (beam) / lag (chord) / torsion modes, FCS, Pilot, Actuator Dynamics.

The whirl flutter phenomenon is driven by high speed and high inflow across the rotor disk, then the axial flow conditions (AP mode and VTOL mode at high speed and low nacelle angles) are the most affected by this phenomenon.

The geometry of the ATA tiltrotor configuration can influence this phenomenon, which needs to be considered carefully, designing the wing with a multidisciplinary approach.

The Air & Ground Resonance is characterized by the blade lag mode coupled with landing gear modes or low frequency airframe modes. Typically, to design-out this kind of instabilities the proprotors are stiff in-plane, and are therefore not subject to ground resonance (mechanical instability on ground).

Other on-ground instabilities include the so-called High- and Low-Focus Roll modes (HFR and LFR), caused by the coupling of the low frequency aircraft modes with landing gears, FCS and the pilot, who closes a loop without intentionally apply control inputs. In fact the aircraft -when on ground- is characterized by low frequency lateral/roll modes referred to as LFR and HFR. The lateral/roll motion of the aircraft in this low frequency mode can cause both FCS feedback inputs and pilot lateral stick inputs as mechanical response, thus causing differential collective input to the rotors. This in turn produces differential rotor thrust leading to more lateral/roll of the aircraft, and hence larger stick inputs. The FCS feedback and the pilot biomechanical feedback can lead to instability if the mechanical feedback gain is high.

The proprotors are affected by the classical isolated rotor phenomena affecting the helicopter rotors, which are not specific of the ATA tiltrotor configuration and are not discussed here.

The ATA configuration, characterized by a light nacelle, a lean wing and an outer wing, has specific dynamic aspects that need to be carefully considered in the conceptual and preliminary design phases, with focus on some particular aspects. In particular the increase of the aspect ratio, also related to the introduction of the outer wings, reduces the first elastic modes frequencies, possibly requiring high stiffnesses in order to avoid aeroelastic instabilities. The removal of large masses from the nacelle (i.e., the engines) and the installation of all the fuel tanks in the fuselage, on one hand, partially mitigates the lowering of the first elastic mode frequency but, on the other side, reduces the inertial forces on the wing. This may increase the overall strains in the structure in particular conditions, increasing the required structural weight. In conclusion, the wing feasibility was assessed and confirmed, and key effects to monitor during the subsequent design phases were identified.

For what concerns the design of the V-tail, the configuration selected so far is similar to previous LHD experience and it is manageable provided that the aft fuselage design, in particular the interface structure between the tail fins and the fuselage, is designed to provide high stiffness while minimizing the structural weight. The overall aircraft CG envelope would benefit from this.

The risks associated to the V-tail configuration are more related to the dynamics and aeroelastic behavior: high aspect ratio of the tail fins reduces the frequency placement of the fundamental dynamics of the structure, making it more susceptible to dynamics loading conditions (gust, landing, buffet) which can become the driving load cases while being more complex to estimate at conceptual level. For what concerns the aeroelastic stability, the configuration is exposed to risks due to flutter mechanisms based on coupled bending and control surface dynamics, which can be addressed by proper tuning of the actuation chain stiffness.

The drive system dynamics is characterized by the rotor and drive train inertia, engine characteristics and engine control system. The dynamics of the drive train is specific to the ATA tiltrotor configuration, due to the different engine location, but is not expected to pose significant challenges as the main elements are similar to the components developed for already established designs by Leonardo Helicopter Division.

10. THE ATA APPLICATIVE ADVANTAGES AND OPPORTUNITIES

The ATA design described in the above pages is of course at this stage a paper aircraft ready for real world testing. However, first confrontations with experience operators, both inside and outside Leonardo, seem to confirm actual advantages foreseen in the early design phases. Moreover, the paper and virtual testing performed on the design have also spotted unforeseen possibilities, related to some of the original configuration elements, which in turn have been included in the concept requirements and have stimulated some design refinement.

- **Non-tilting engine**: confirming the 4th gen design and in continuity with Leonardo NGCTR experience; large availability of engines, in particular in the 2000-3000 hp class, no deck/terrain hot gas effect, easier maintenance, irrespective of nacelle tilt angle

- **Survivability**: in addition to the aerodynamics and inertia aspects described above, the wing-root location of the engines has operative advantages for survivability/detectability, because of the intrinsic engine screening provided by wing and fuselage;

- **Maintenance**: the central engine installation could also help in maintenance operations because the ground crew works close to the fuselage and maintenance can be performed also in folded configuration

- **Engine growth potential**: on a tiltrotor, the complex aeroelastic design of the wing is fundamentally linked to the nacelle inertia, so a change in the engine implies for sure an aeroelastic re-evaluation or even a physical redesign of the whole wing. The engine wing-root installation, decoupled from the wing, solves this problem as a whole and allows all options for in-service engine upgrade and growth.

- **Austere environment**: the engine wing-root installation, outside of the rotor downwash and forward-oriented, reduces the FOD and dirt ingestion

- **Hybridization**: the central powerplant installation is a fundamental enabler of an hybrid tiltrotor, with a thermal power generation, distributed electrically to the proprotors, in lieu of a mechanical drive train. This allows simplification of the mechanical drivetrain and enables some operative capabilities such as a simpler wing folding or an optimized rotor performance in cruise.

The ATA concept has been studied at Leonardo for a few years, resulting in a few patents (ref. 4,5) and in several applications as basis for research projects where innovation in tiltrotor technology is envisaged and at the same time where analyses and evaluation can increase the TRL and the maturity of the idea.

Among other Company evaluation and studies, since 2022 the ATA concept has been also used as a kind of analytical testbench of the Leonardo – Politecnico di Milano shared initiative called “ThesisLab”, which aims at a joint industry-university evaluation of Tiltrotor technologies through the technical contribution of academic staff and Master degree students in Aeronautical Engineering. Over the last years, this project focused on multidisciplinary studies concerning Structural design, Airframe and Rotors Aeroelasticity, Aerodynamics, Flight Mechanics, Flight Controls, Rotors design, Powerplant & Drivetrain and Model Based System Engineering.

The lightweight nacelle, whereas it is an advantage for roll and yaw inertia reduction, it is detrimental for VTOL pull-up maneuvers in which the inertia relief is reduced and therefore the stress associated to the wing root bending becomes a driving parameter of the wing design. Indeed, with respect to a 3rd or 4th generation tiltrotor of the same MTOW, most of the mass is in the fuselage and generally close to the longitudinal axis. This aspect needs to be carefully considered upfront at the early stages of the wing design to make sure that loads and whirl flutter requirements are considered and met.

One of the risks associated to the ATA configuration is the location of the fuel storage: the wing, kept lean and with low aspect ratio for performance purposes, it is not an effective solution for large fuel tanks, which could be located in the fuselage and below the cabin floor. This solution is quite efficient but brings some risks and drawbacks: for stability and controllability purposes the weight and CG shall be monitored in flight and the fuel must be carefully managed to ensure the CG is kept within the allowed envelopes; the height of the cabin floor with respect to the ground would be increased to include the fuel tanks volume,

Figure 13: rendering of a possible ATA concept application, showing a disaster relief mission scenario, where speed and vertical flight capabilities are a key success factor.

11. THE ATA RISKS AND CHALLENGES

The ATA configuration described above brings certainly a series of advantages, but it pays the toll of a few risks associated to its own specific characteristics, briefly discussed here.

so the overall aircraft aerodynamics drag is slightly increased due to the increase frontal area.

12. CONCLUDING REMARKS

The Advanced Tiltrotor Aircraft is a concept developed by Leonardo as a result of more than 40 years of explorations in tiltrotor design.

The goal of the whole concept is to improve the mission and operational capabilities of a tiltrotor, keeping the same cost/complexity implied by the transformative configuration.

To achieve this goal, the concept is focused on aerodynamic efficiency, download minimization, weight and inertia reduction, adopting several features such as a central powerplant, an outer tilting wing section, a three-surface configuration and a rear ramp.

Being in a conceptual phase, the Advanced Tiltrotor Aircraft has still low maturity: no product or demonstrator has been built to date and the integration of all the features has not been physically tested yet. On the other hand, it can be said that the ATA is based on the integration on -a novel configuration- of proven technologies, often already applied on existing products, with clear benefit on the maturation of the concept.

Finally, over the last years, a build-up of evidence coming from numerical simulations of specific experimental tests started confirming the value of the concept and more results are expected shortly.

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13. ACKNOWLEDGMENTS

The authors want to express their gratitude to all the colleagues who over the years have contributed to this concept, in particular: Valentina Giuliani, Andrea Bavetta, Andrea Bianchi, Sergio Sartori, Alessandro Scandroglio, Alberto Trezzini, Andrea Mancini, Daniele Amato, David King, Pierre Abdel-Nour, Andrea Cristina, Scott Dubeck.

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