DEVELOPMENT OF A NEW GENERATION ROTOR FOR TILTROTORS

From Preliminary Design to Flight Test Readiness

Andrea D'Andrea
andrea.dandrea01@leonardo.com
Head of Rotor Systems Technical Area
Leonardo Helicopters Division

ABSTRACT

The Enhanced Tiltrotor blade, also known as the RGF3 blade, represents a major milestone in Leonardo Helicopters Division's pursuit of advanced rotorcraft technology. Developed at the Yeovil facility in the United Kingdom as part of a dedicated program and in collaboration with the European Clean Sky 2 initiative, it is a key enabler for the Next Generation Civil Tiltrotor Technology Demonstrator. Leveraging the AW609 airframe, the NGCTR integrates a new lateral rotor control system and a V-tail with ruddervators to expand maneuverability and control authority. The RGF3 blade combines aerodynamic efficiency with manufacturability, cost effectiveness, and certification readiness. Innovations include advanced airfoil families, highly swept anhedral tips, dual-redundant anti-ice systems, and full compatibility with legacy components. A comprehensive test campaign—covering structural loads, lightning and bird strikes, icing, and wind tunnel validation—confirmed its robustness and performance. The RGF3 blade embodies Leonardo's vision for high-speed, sustainable, and reliable next-generation rotorcraft.

1. INTRODUCTION

The development of the Enhanced Rotor Blade, referred to internally as the RGF3 blade, represents a strategic leap in Leonardo Helicopters Division's (LHD) commitment to the advancement of tiltrotor technology. Born out of the collaborative Clean Sky 2 (CS2) research initiative funded by the European Commission, this program focuses on sustainable, high-performance, and operationally flexible aircraft. In particular, the RGF3 blade has been developed to meet the rigorous demands of the Next Generation Civil Tiltrotor (NGCTR) Technology Demonstrator (-TD), a full-scale experimental aircraft designed to validate revolutionary rotorcraft technologies.

The Clean Sky 2 program (Ref. 1) was launched in July 2014 as a continuation of Europe's long-term investment in cutting-edge aeronautics. Within the CS2 framework, Leonardo has played a leading role in the Fast Rotorcraft platform, aiming to create a tiltrotor aircraft capable of exceeding 300 knots, operating at altitudes up to 25,000 feet, and supporting a broad range of missions including civil passenger transport, search and rescue, offshore logistics, and medical evacuation. The NGCTR is being designed with a pressurized cabin, advanced wing and tail configurations, and a unique rotor system tailored to both vertical and horizontal flight regimes.

The NGCTR-TD will initially leverage an AW609 airframe as a donor platform, enabling rapid integration and validation of new components. Among the most significant modifications is the introduction of a new lateral rotor control system, paired with a redesigned V-tail featuring ruddervators. These upgrades enhance maneuverability and control authority across the aircraft's extensive flight envelope.

In parallel with the CS2 activities, LHD initiated a dedicated rotor blade development program at its Yeovil facility in the United Kingdom. This initiative was aimed at addressing not only aerodynamic performance but also key factors such as manufacturability, cost efficiency, and certification readiness. The result is the RGF3 blade, a next-generation solution optimized for interchangeability with legacy systems, while incorporating modern design philosophies and novel materials to improve lifecycle supportability.

This paper presents the complete design, testing, and validation journey of the RGF3 blade, starting from initial concept and requirements definition, through numerical optimization and experimental verification (blade structural testing, lighting strike, bird strike, performance and ice wind tunnel testing), and culminating in flight test readiness. Emphasis is placed on the aerodynamic, structural, and thermal innovations embedded in the blade, including advanced airfoil families, highly-swept anhedral tips, dual-redundant anti-ice systems, and a manufacturing strategy that achieves nearly an order of magnitude cost reduction compared to previous generation blades. Ultimately, the RGF3 blade embodies Leonardo's strategic vision for next-generation rotorcraft: one that harmonizes high-speed performance, safety, reliability, and sustainability. Its development stands as a cornerstone of the NGCTR program and exemplifies how focused research and technological synergy can drive meaningful innovation in aerospace design.

2. NGCTR TECHNOLOGY DEMONSTRATOR OVERVIEW

The Next Generation Civil Tiltrotor (NGCTR) Technology Demonstrator (-TD) represents a pivotal technological leap for Leonardo Helicopters Division under the Clean Sky 2 initiative (Fig. 1). Conceived as a full-scale, non-commercial aircraft, the NGCTR-TD serves as a critical testbed for evaluating and validating future vertical lift technologies aimed at high-speed, efficient, and sustainable flight. The demonstrator integrates a broad array of innovations—structural, aerodynamic, and propulsion-related—intended to inform future production models for civil and dual-use applications.

Figure 1 – NGCTR-TD aircraft

One of the NGCTR's most distinctive features is its non-tilting engine configuration. Unlike legacy tiltrotors such as the V-22 Osprey or AW609—where entire nacelles rotate to transition between helicopter and airplane modes—the NGCTR keeps its engines fixed. Only the rotor shafts articulate, significantly simplifying the design. This architectural choice eliminates the need for engines capable of vertical operation, thereby reducing mechanical complexity, improving maintainability, and expanding the potential for using a broader range of commercially available turboshaft engines.

The NGCTR's airframe incorporates a straight, unswept wing with zero dihedral, designed to simplify the layout of the interconnecting shaft system that synchronizes the two rotors. This configuration enhances mechanical reliability and facilitates efficient power transfer across the wing. Large, movable flaps augment the wing design by reducing rotor download in hover, which boosts lift, and by facilitating smoother transitions to forward flight. These flaps help expand the conversion corridor—a critical regime where the aircraft transitions from vertical to horizontal flight—enhancing safety and stability.

Tail configuration options have also been under active exploration, with the current focus on a V-tail featuring ruddervators. This arrangement reduces aerodynamic drag and improves trim performance while maintaining necessary control authority across different flight modes. The integration of proprotor-driven yaw control with the V-tail surfaces introduces a new level of aerodynamic fine-tuning not previously available in traditional tiltrotor or fixed-wing platforms.

Complementing the aerodynamic advancements is the introduction of a modular, distributed fly-by-wire Flight Control System (FCS). Departing from conventional centralized architectures, the NGCTR's distributed FCS increases redundancy, adaptability, and fault tolerance. Its modular nature allows for scalable system configurations tailored to different aircraft roles, while ensuring precise control over the aircraft's complex flight dynamics—particularly during transitional phases.

For its flight test phase, the NGCTR-TD leverages a modified AW609 fuselage as a donor platform. Though some full-scale behaviors, such as whirl flutter response, may not be entirely replicated, the demonstrator enables comprehensive validation of core technologies. In July 2024, the NGCTR-TD achieved a major milestone with its first successful ground run at the Cascina Costa facility in Italy, verifying mechanical integrity and responsiveness of the new rotor systems. Its first flight is targeted for Q4 2025, followed by an intensive 200-hour flight test campaign covering the full operational envelope.

Overall, the NGCTR-TD is not merely a technology demonstrator—it is the physical embodiment of Leonardo's long-term strategy to redefine tiltrotor aviation. By integrating forward-looking aerodynamics, simplified mechanical systems, and next-generation flight control and rotor technologies, the NGCTR sets a new benchmark for vertical lift performance, sustainability, and system-level efficiency.

3. NGCTR ROTOR SYSTEM EVOLUTION

The evolution of the rotor system for the NGCTR Technology Demonstrator (NGCTR-TD) marks a significant technological progression from legacy tiltrotor configurations. Building on decades of experience with the AW609 program, Leonardo Helicopters Division has spearheaded the design and development of an advanced rotor system that not only enhances performance in hover and cruise but also simplifies manufacturing and maintenance while reducing operational costs.

Figure 2 –New generation Enhanced Tiltrotor Blade (also known as the RGF blade)

The foundation of this evolution is the RGF3 rotor blade (Fig. 2), developed under a parallel rotor system enhancement initiative headquartered at Leonardo's Yeovil facility in the United Kingdom. Although developed in alignment with Clean Sky 2 (CS2) objectives, the RGF3 blade program was initiated as an independent effort to fast-track key improvements in aerodynamic performance, structural resilience, and production scalability.

One of the core design tenets of the RGF3 program was maintaining backward compatibility with existing donor rotor hubs and interfaces. This decision allowed the new blade to be tested using the AW609-sized NGCTR-TD airframe without necessitating a complete redesign of the rotor assembly. The RGF3 blades preserve the same radius, weight, static moment, and key geometrical limits as their predecessors, enabling seamless integration while preserving the aircraft's original flight envelope and dynamic behavior.

In addition to the new blade geometry, significant modifications were introduced at the system level. A new lateral rotor control system has been integrated into the NGCTR-TD platform. This addition offers improved maneuverability, particularly during hover and low-speed flight, by enabling direct lateral thrust vectoring. Complementing this system is a new V-tail equipped with ruddervators, which, in conjunction with lateral rotor control, enhances yaw authority and overall stability throughout the aircraft's flight envelope.

The RGF3 blade incorporates a suite of aerodynamic innovations tailored to enhance tiltrotor performance across both hover and cruise regimes. A highly swept anhedral tip reduces tip vortex drag while mitigating compressibility effects, improving efficiency at high speeds. The blade also employs a non-linear twist distribution, carefully optimized to deliver balanced lift along the span, reducing induced drag and enhancing stability. Complementing these features are proprietary AMDX airfoil sections, developed specifically for tiltrotor applications that improve performance margins under demanding conditions. Collectively, these design elements yield measurable aerodynamic benefits: hover efficiency gains of 3–4% and cruise (propeller mode) improvements of up to 5% at peak conditions. They also enable a significant delay in stall onset under high disk loadings and strongly suppress performance divergence at very high forward speeds. These characteristics render the RGF3 blade fully capable of supporting tiltrotor operations up to 350 knots, ensuring both robustness and efficiency.

Structurally, the RGF3 blade is designed to meet stringent strength and fatigue requirements under extreme load conditions typical of tiltrotor operations. Key material selections include high-temperature cure carbon and glass epoxy composites, with the spar constructed using a foam-filled, D-shaped architecture for enhanced stiffness and structural integrity. Importantly, the blade design also accommodates redundant heater mats for ice protection and includes embedded copper mesh for lightning strike survivability and erosion shields.

Through the RGF3 initiative, Leonardo has demonstrated that high-performance rotor systems can be developed without sacrificing compatibility, maintainability, or cost-effectiveness, being a foundational element for future aircraft configurations.

The rotor system evolution described here is pivotal to the NGCTR's goal of validating next-generation technologies. By combining aerodynamic refinement, structural innovation, and system-level enhancements, Leonardo has laid the groundwork for a rotor architecture that is simultaneously high-performing, modular, and ready for the future of vertical lift aviation.

4. ENHANCED ROTOR BLADE DESIGN FEATURES

The RGF3 blade is at the heart of Leonardo's strategy to enhance tiltrotor performance, maintain design modularity, and reduce lifecycle costs. Its design synthesizes aerodynamic innovation with structural pragmatism, meeting the dual demands of high-speed cruise and low-speed hover. This section details the defining features of the blade geometry, aerodynamic characteristics, and their operational impacts.

One of the most prominent aerodynamic advancements is the highly swept anhedral blade tip. Unlike conventional straight or singly-swept tiltrotor blade-ends, the RGF3 blade tip includes a double-sweep configuration that enhances performance by mitigating compressibility effects during cruise and reducing tip vortex drag in hover. This unique tip geometry also incorporates an anhedral angle, which helps maintain flow attachment and minimize rotor download, particularly in hot-and-high conditions where hover performance is critical.

The blade's spanwise twist distribution represents another key innovation. Rather than adopting a traditional tiltrotor blade bi-linear twist profile, the RGF3 blade features a non-linear twist optimized through multi-objective aerodynamic analysis. This profile improves the lift distribution across the span and delays blade stall onset, enhancing rotor control and efficiency at high disk loadings. These benefits directly translate into increased thrust generation and reduced power requirements in vertical lift modes.

The aerodynamic performance of the blade is further elevated through the integration of Leonardo's proprietary AMDX airfoil family. These airfoils have been specifically tailored for tiltrotor applications, balancing the competing needs of low-speed high-lift and high-speed drag reduction. Spanning from root to tip, the airfoils exhibit a gradual variation in thickness and camber, enabling structural support near the root while minimizing compressibility penalties toward the blade tip.

In support of operational flexibility, the RGF3 blade includes features designed for environmental resilience. Dual-layer electro-thermal heater mats are embedded in the leading edge to provide anti-icing and de-icing capabilities. These mats are arranged in redundant, independently powered zones, meeting safety-of-flight standards for operations in known icing conditions. Lightning protection is provided through an integrated copper mesh that connects to external erosion shields made of titanium and electroformed nickel.

In summary, the RGF3 blade integrates cutting-edge aerodynamic shaping with practical design constraints to deliver a high-performance, low-maintenance solution for modern tiltrotor operations. Its enhanced lift, reduced drag, and adaptive geometry support a broad mission envelope while complying with rigorous safety and certification requirements.

4.1. Design methodology and Optimization framework

The design of the RGF3 blade was driven by a comprehensive numerical optimization process built around the need to satisfy multiple and sometimes conflicting requirements. These included performance enhancement across all flight regimes, structural integrity under extreme loading, integration with legacy systems, and compatibility with cost-effective manufacturing processes. To achieve these goals, Leonardo Helicopters employed an advanced design framework integrating high-fidelity aerodynamic, structural, and flight mechanics tools within an automated, iterative optimization loop. In this section a brief review of the integration of rotorcraft simulation software with complex aeromechanical models developed in recent years in Leonardo, which can provide increased fidelity and functionality of the system as compared to any of the individual tools, will be presented.

Continued advancement in computational resources allows nowadays coupled codes to be executed efficiently and even in real-time. From an aerodynamic/aeroacoustic point of view present numerical chain is based on the use of a state-of-the-art Genetic Diversity Memetic Algorithm (GDMA, Ref. 2), a surrogate-assisted multi-objective optimizer developed by Leonardo. GDMA combines evolutionary search strategies with local gradient-based refinement and uses artificial neural networks (ANNs) as surrogate models to reduce the computational burden of high-fidelity simulations. This approach allows for rapid exploration of complex design spaces while maintaining accurate predictions of aerodynamic and structural behavior.

The GDMA tool was coupled with several aerodynamic solvers (Fig. 3) like: ADPANEL, a Multi-Processor Unstructured Panel Code Coupled with a CVC-Free Wake Vortex Mode (Ref. 3-7) for isolated rotor and interactional rotor-airframe aerodynamic and aeroacoustic analysis, HMB (Ref. 8) and Fluent (CFD Navier-Stokes tools) for 2D airfoils optimization and more reliable 3D rotor analysis in every flight conditions – especially at high speeds in airplane mode to properly capture transonic effects.

The integrated computation design chain was firstly used to design a new-generation family of blade airfoils (AMDX) for tiltrotors which was demonstrated to offer, in comparison with LHD family tiltrotor-legacy airfoils: improved performance in terms of maximum lift coefficients positively affecting thrust capabilities and maneuverability of the aircraft; stall incidences which have been maintained or delayed; equal or lower drag coefficients on the typical operative conditions; low pitching moments.

Secondly, the computational chain was then used to optimized the blade planform; the optimization objectives were configured to maximize Figure of Merit (FoM) in hover, minimize drag in propeller mode, and ensure robust lift generation at high altitudes and low speeds. These objectives were evaluated under multiple flight conditions, including hover at sea level, hover in hot-and-high scenarios, and cruise at speeds up to 320 knots.

The optimization process started from the parameterization of the blade characteristics by means of B-spline curves; they have a quite simple mathematical representation and allow to create curves with high flexibility, which means the possibility to change the curve's order to vary its smoothness and control the curve with any finite number of control points. The four features that were controlled during the optimization were: twist, chord, sweep and anhedral. Following airfoil design optimization loop, the full blade geometry was optimized through iterative refinement, with hundreds of simulations executed to converge on a Pareto-optimal design set. The selected configuration achieved a non-linear twist profile and a double-swept anhedral tip that provided substantial gains in performance, validated through both simulations and wind tunnel testing. CFD analyses confirmed consistent improvements in rotor efficiency and reduced aerodynamic penalties in critical regimes with respect to the legacy blade.

Structural integrity of the blade and aeroelastic stability of the rotor/airframe were assessed for every single blade configuration which was adjacent to the final Pareto curve using CAMRAD II (Ref. 9) and Leonardo's proprietary GyroX II and MASST tools (Ref. 10). These simulations ensured the blade met strength, vibration, and flutter constraints throughout the envelope.

4.2. Design of AMDX Airfoil Family and 2D Wind Tunnel Airfoils testing

The AMDX airfoil family represents a foundational advancement in the aerodynamic design of the RGF3 blade, enabling performance improvements across multiple flight regimes. The AMDX series was conceived, optimized, and validated entirely by Leonardo Helicopters to provide full design control and application flexibility for future tiltrotor platforms especially for operations at very high-speeds (> 320kts).

The need for a dedicated airfoil family stemmed from both technical and strategic requirements. The airfoils used in existing and past tiltrotor blades designs were conceived for earlier mission profiles and were not optimized for the dual-mode demands of next-generation tiltrotors with capability to be efficient up to flight speeds of around 350kts.

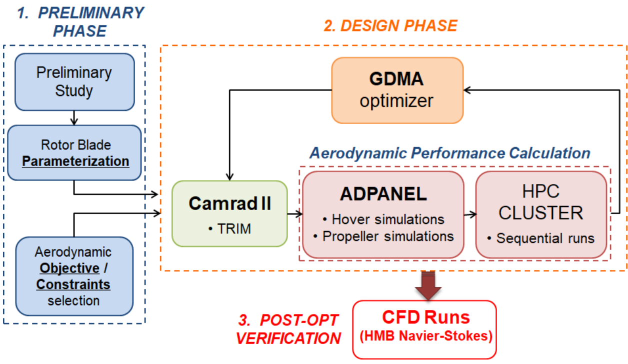

Figure 3 – Aerodynamics/Aeroacoustics optimization design process of new rotor blades by means of state-of-the-art Genetic Diversity Memetic Algorithm (GDMA)

In contrast, the AMDX family addresses modern requirements: improved lift in hover, reduced drag at cruise, robust transonic behavior, and manufacturability across varying thickness profiles.

The development of AMDX airfoils was carried out using a multi-objective optimization framework that incorporated aerodynamic solvers such as ADPANEL, Fluent, and MSES, combined with the Genetic Diversity Memetic Algorithm (GDMA) for parameter space exploration. The optimization goals included maximizing lift-to-drag ratio, maintaining low pitching moments, and enabling smooth surface transitions suitable for composite blade construction. Five distinct airfoil thicknesses were developed—ranging from 39% to 8.35%—to match the radial requirements of the RGF3 blade.

Each airfoil in the AMDX family was tailored to a specific blade radial station:

- AMDX3900A (39% thickness) for the root region, offering structural support and internal volume for pitch mechanisms;
- AMDX3000A and AMDX2000A for transition zones, balancing structural needs with aerodynamic efficiency;
- AMDX1501A and AMDX1200A for mid-span performance in hover and cruise;
- AMDX0912B and AMDX0835B for tip regions, reducing compressibility effects and enabling anhedral shaping.

Following numerical optimization, the airfoils were validated through wind tunnel testing and CFD analysis. Wind tunnel tests were conducted at the ARA 2.74m x 2.44m Transonic Wind Tunnel in Bedford, UK (Fig. 4 and 5). These tests confirmed that the new profiles achieved higher maximum lift coefficients, lower drag at operational Mach numbers, and delayed stall onset compared to legacy designs. The objective of the tests was to understand compressibility effects, shock formation, and drag behavior at high speeds. Test parameters included:

- Mach numbers ranging from 0.3 to 0.85
- Angles of attack from −5° to +12°
- Pressure distribution and drag coefficient measurements

The testing validated that AMDX profiles delay shock-induced drag rise, reduce peak suction pressures, and maintain attached flow at higher angles of attack. These characteristics were particularly pronounced on the outer blade sections, where sweep and anhedral geometries combine with the airfoil's inherent design.

The airfoils were further validated in the context of the complete RGF3 blade through CFD simulations using the HMB Navier-Stokes solver, confirming their favorable aerodynamic characteristics under real-world blade loading conditions. The tip airfoils demonstrated reduced vortex formation and better flow attachment at high speed, while the root and transition sections provided sufficient thickness for structural continuity and internal systems.

Overall, the AMDX airfoil family has proven critical to the success of the RGF3 rotor blade. Its performance and versatility affirm Leonardo's capacity to independently design, optimize, and validate advanced airfoils for next-generation tiltrotor applications. The AMDX series is poised to serve as a core aerodynamic asset for both current and future vertical lift platforms.

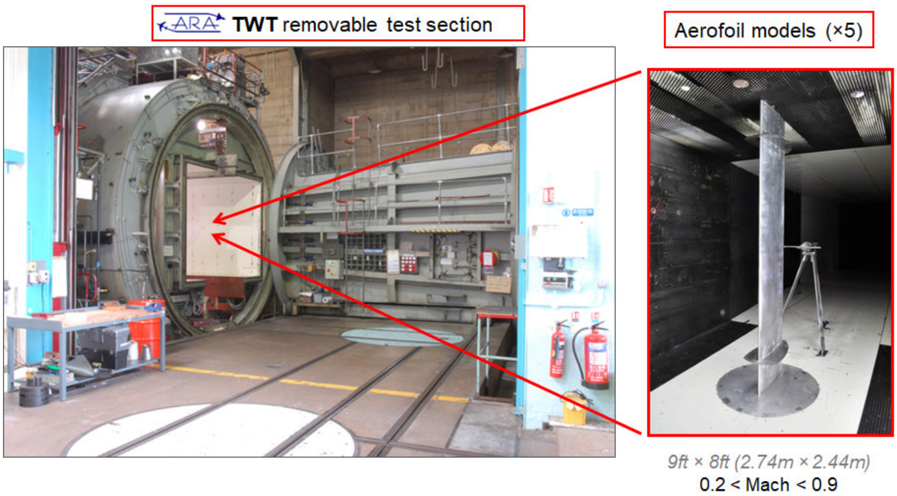

Figure 4 – Wind Tunnel tests (ARA 2.74m x 2.44m Transonic Wind Tunnel in Bedford, UK) of the ADMX family airfoils

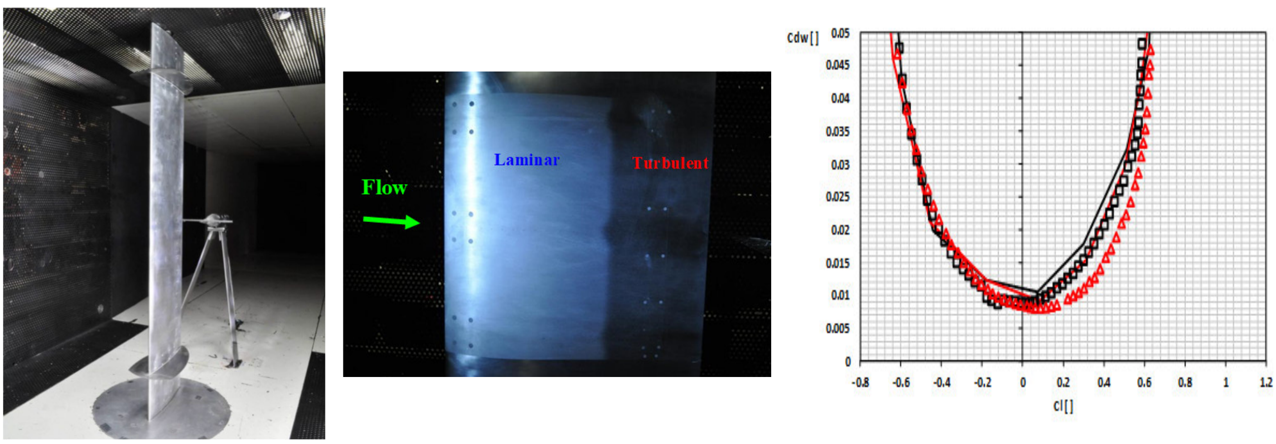

Figure 5 – AMDX family airfoils testing at the ARA 2.74m x 2.44m Transonic Wind Tunnel in Bedford, UK (left, center). Comparison between Drag exp. data [scatters] and CFD predictions [lines] for a specific airfoil before and after its shape optimization – blade: legacy airfoil; red: AMDX airfoil (right).

4.3. Post-design validation with CFD and Wind Tunnel Rotor testing

Following the completion of the RGF3 blade design process, a comprehensive post-design validation phase was conducted using high-fidelity CFD simulations. These analyses aimed to confirm the aerodynamic performance improvements predicted by lower-order models and to investigate blade behavior under full-scale, real-world flow conditions. The Helicopter Multi-Block (HMB, Ref. 8) solver served as the primary CFD tool, offering Navier-Stokes resolution with rotor-specific capabilities suited to complex geometries and transitional flight regimes.

Hover Mode CFD Validation: In hover, the CFD simulations focused on thrust, torque, and wake behavior across a range of collective pitch settings (from 8° to 15°, at different RPMs). The optimized RGF3 blade demonstrated:

- o Improved thrust-to-power ratios at both sea level and high-altitude conditions;
- o Delayed onset of flow separation at inboard sections;
- o Delayed onset of blade tip flow separation at high disk loadings;
- o Around a 4% increase in maximum Figure of Merit;
- o Smoother and more coherent tip vortex structures.

As shown in Figure 6, which presents the Figure of Merit (FM) for different collective inputs of the enhanced rotor (red curve) compared with a notional baseline (black curve) that blends existing tiltrotor configurations, the enhanced design not only achieves a higher maximum FM but also demonstrates a clear ability to delay stall onset. This results in up to a 15% increase in the operational range of thrust coefficients (Ct).

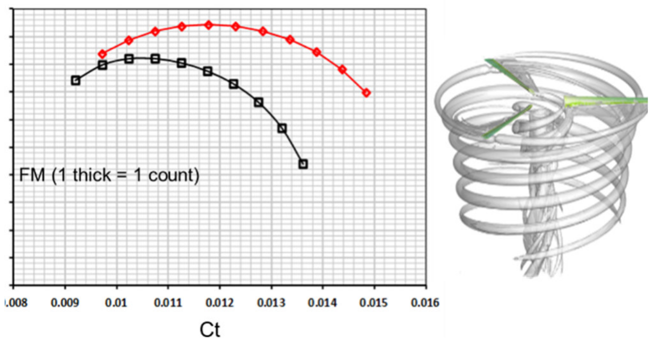

Figure 6 Figure of Merit (FM) vs Ct curve of the enhanced rotor (red) vs. baseline configuration (black)

Notably, the RGF3 blade's swept anhedral tip caused the vortex to rise higher and remain more detached from the following blades, reducing interference and associated unsteady loads. This behavior is particularly advantageous for vibration reduction and acoustic performance in hover.

Figure 7 presents the pressure coefficient distribution (Cp) along the blade span for both the enhanced and baseline configurations at two collective inputs, trimmed to thrust coefficients of Ct = 0.010 and Ct = 0.016, respectively. The plots also include skin-friction lines, which clearly highlight the enhanced blade tip's ability to delay tip-flow separation under high disk loading conditions (Ct = 0.016). Moreover, at low-to-medium collective settings (Ct = 0.010), the double-sweep anhedral tip of the enhanced blade remains free from shock-wave formation on the upper surface, demonstrating improved aerodynamic performance across the operating range.

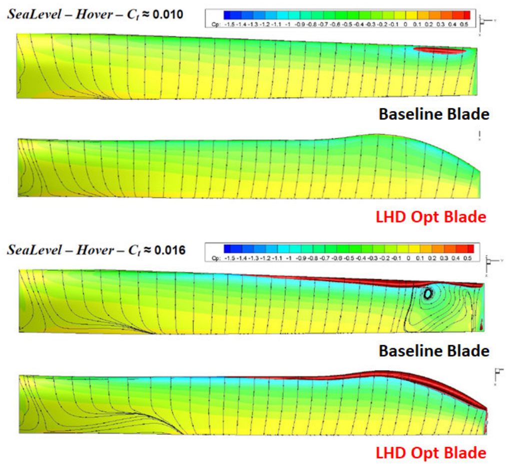

Figure 7 Pressure coefficient and skin friction lines distribution along the spanwise of the enhanced and baseline blade at Ct equal to 0.010 and 0.016

Propeller (Cruise) Mode CFD Validation: Several simulations were carried out in isolated rotor conditions at forward flight speeds ranging from 240 to 350 knots. Globally, CFD results showed the enhanced blade to offer:

- o Improved thrust-to-power ratios at both sea level and high-altitude conditions
- o Reduced supercritical flow regions and shock intensity on upper blade surfaces
- o Up to 6% increase in cruise propeller efficiency for speeds lower than 300kts; up to 9-10% increase in cruise propeller efficiency for speeds from 320 and 350kts

As an example, the next Figure 8 shows the propeller efficiency (η_p) distribution at different values of thrust coefficient (Ct) at 280, 320 and 350kts for both the enhanced (solid) and baseline (dotted) configurations. The decay of rotor efficiency with the increasing of transonic effects on the blades is very well evident going from 280 to 350kts for the baseline blade, while remains very well mitigated for the RGF3 blade. This is due to a reduction of compressibility effects at the tip region (highly swept and tapered, with anhedral) which improved also noise emissions. The RGF3 new technology is therefore shown to be suitable for next generation Tiltrotors being able to maintain very high efficiency up to 350kts aircraft speed.

These effects result in enhanced fuel efficiency, reduced engine power demands, and increased operational ceiling—especially critical for high-altitude and hot-day missions. Thanks to a maximum rotor propeller efficiency which is almost constant in the range 280-320kts, the new blades is shown to be designed to support cruise missions beyond 300 kts.

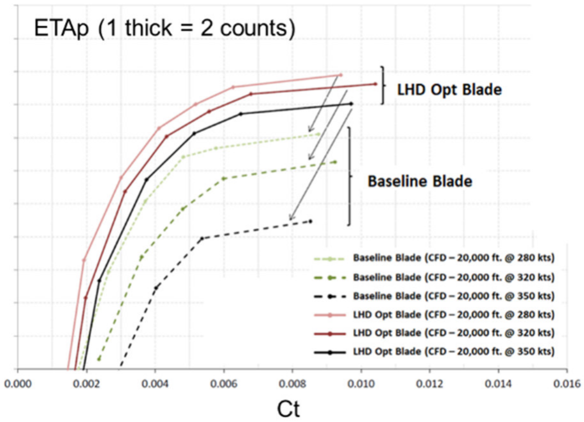

Figure 8 Propeller efficiency (η_p) vs. Ct curves at 280-320 and 350kts. Solid curves = enhanced blade; dotted curves = baseline blade

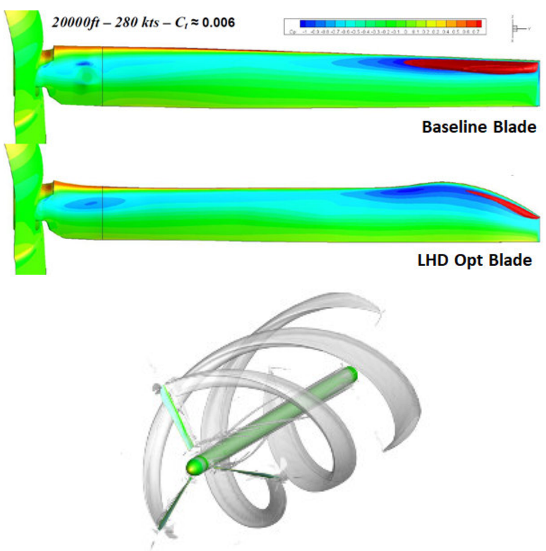

Figure 9 Pressure coefficient distribution along the spanwise of the enhanced and baseline blade at Ct = 0.006 (280kts, 20,000ft)

Wake and Flow Structure Analysis: HMB simulations produced detailed visualizations of blade tip vortices and wake interaction. Compared to legacy blades, the RGF3 configuration exhibited:

- A cleaner, longer-lasting wake with fewer unsteady flow features
- Lower tip vortex strength and reduced induced drag
- Mitigation of negative torque spikes at inboard sections in high-speed flights. The simulations also revealed that pressure fluctuations along the blade span were more evenly distributed, a result of the non-linear twist and airfoil variation implemented in the RGF3 design. These characteristics directly contribute to improved dynamic stability and control responsiveness.

Wind Tunnel testing Validation: Wind tunnel testing has played a pivotal role in validating the aerodynamic design and performance of the RGF3 blade throughout its development. These campaigns provided critical data for calibrating simulation tools, verifying optimization outcomes, and ensuring compliance with design goals under both hover and cruise conditions.

A performance assessment wind tunnel test campaign was conducted at Politecnico di Milano (POLIMI) open-jet low-speed wind tunnel which was aimed at characterizing the rotor's performance in hover and VTOL helicopter mode (at slow speed), where vertical lift and power efficiency are most critical. A scaled rotor model (scale 1:4) was built by LHD using geometrically accurate replicas of the RGF3 blade, was mounted on a test rig that allowed collective pitch variation and accurate thrust/power measurements (Fig. 10).

Test parameters included:

- Collective pitch variation from 8° to 15°;
- Rotor rotational speeds corresponding to NGCTR-TD operating conditions;
- Figure of Merit (FoM) – in hover, rotor thrust and torque values, and blade pressure measurements

Key findings from wind tunnel campaign in VTOL mode confirmed in full the results from the CFD. In particular they demonstrated (Fig. 11):

- Enhanced performance at high disk loading, supporting hot/high takeoff conditions;
- Reduced power requirements at similar thrust levels, confirming improved aerodynamic efficiency.

Additionally, pressure taps, strain gauges, and flow visualization techniques (e.g., tufts and smoke lines) enabled detailed insights into aerodynamic loading and flow behavior. These findings informed not only rotor design but also nacelle interface assessments and conversion corridor evaluations.

The results were used to validate and refine lower-fidelity aerodynamic models (ADPANEL, Fluent), which in turn fed into the design optimization loop. Data from both POLIMI test campaign were then used to further calibrate computational tools such as HMB (Helicopter Multi-Block), ADPANEL, and CAMRAD II. The close correlation between wind tunnel and simulation results strengthened confidence in performance predictions and supported key decisions during the blade optimization process.

The increased hovering performance of the RGF3 rotor (with respect to the baseline configuration) obviously translate into higher gross weight capability during vertical takeoff, improved hover out-of-ground-effect (HOGE) performance, and greater safety margins in confined-area operations such as rooftop landings or rescue missions.

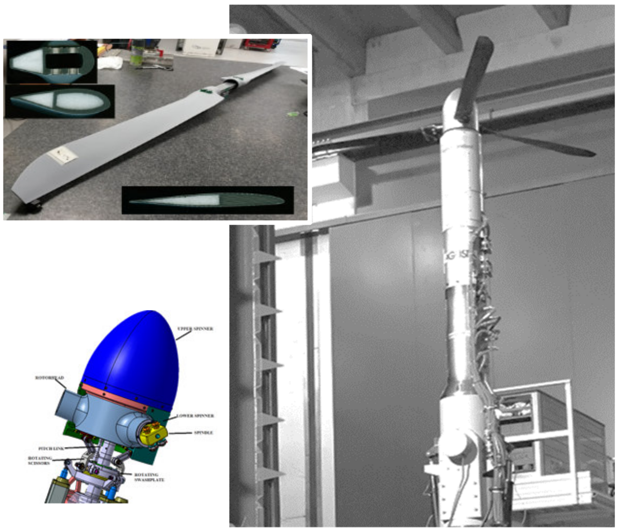

Figure 10 Scaled rotor models (scale 1:4) assembled in POLIMI open-jet low-speed wind tunnel aimed at characterizing rotors performance in hover and VTOL helicopter mode (enhanced vs. Baseline configurations)

4.4. Aeroelastic and Dynamic Design

Insights on the aeroelastic optimization are briefly presented in this section. The requirement to be able to design a rotor blade which was compliant with the necessity to be compatible with the modified rotor system of the donor aircraft, brought to the setting of clear dynamic design constraints. Regarding the integrated mass properties, for example, the total blade mass was not to exceed that of the donor-rotor-blade; the blade interface limit and fatigue loads were not to be increased; the blade 1st moment of mass (i.e. CF load) was not to be increased as well.

The aeroelastic and aeroservoelastic stability requirements give rise to constraints on the stiffness distribution for the new blade, such as:

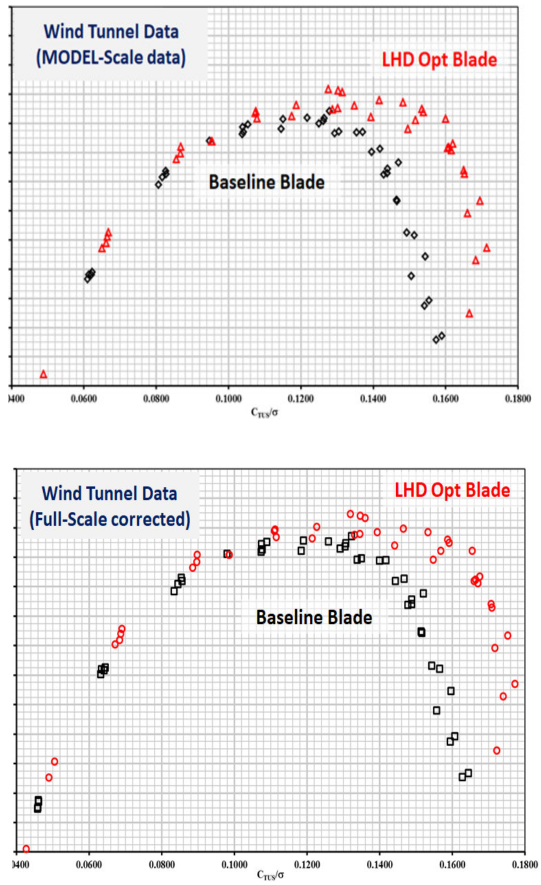

Figure 11 –Example of WT hover test data (model-scale [top] and full-scale [down] corrected) showing the higher performance in terms of Figure of Merit vs. Thrust

- the range of acceptable beam stiffness in the inner part of the blade was constrained at the lower end by blade static strength requirements and at the upper end by aeroelastic stability and fatigue load requirements;
- the range of acceptable chord stiffness was also constrained, firstly by the need to prevent high-speed airplane mode aeroelastic instability (whirl flutter), which is heavily influenced by the fundamental lag mode dynamics at high collective pitch, and also the need to avoid the second rotor harmonic in VTOL mode (low collective pitch) conditions, which would otherwise lead to excessive interface loads.

The setting of previous requirements and constraints (compatibility with donor aircraft rotor) will allow LHD to test a new blade design in flight – on NGCTR-TD - without the need to re-design at the same time all the other rotor components.

The dynamic design challenge was then to work within these significant constraints, providing a design satisfying the stability requirements and minimizing the blade and interface loads whilst allowing for the external profile made desirable by the aerodynamic and flight mechanics requirements. This last point is significant. Legacy tiltrotor blades (AW609, V22 and XV-15) typically employ a trapezoidal planform. The relatively large cross-section at the tip allows for the fitting of balance and inertia weights which allow to easily meet the autorotation inertia requirement whilst not exceeding the mass and 1st moment constraints. For the LHD enhanced blade, incorporating a significant reduction in cross-section at the tip, and due to its peculiar highly-swept anhedral tip, it is not possible to use such inertia weights at the tip, especially as the significant tip sweep would result in those weights being aft of the feathering axis and thus introducing undesirable aeroelastic coupling.

The ability to meet the outlined design challenge of course starts with having available a reliable suite of aeroelastic software tools. For isolated rotor stability assessment, use is made of the CAMRAD II software (Ref. 9). For limit and fatigue loads the propriety LHD tool, GyroX II, is used. This tool has undergone extensive validation against flight data for both helicopter and tiltrotor products. For coupled rotor-airframe aeroelastic stability assessment, use is made again of CAMRAD II in the initial design stages; finally, the fully coupled aeroservoelastic analysis, including all relevant system dynamics such as actuator dynamics, pilot biomechanics and control laws is performed using the MASST software (Ref. 10). All of the software tools introduced in this work have been validated using the wealth of available tiltrotor test data such as that gathered during the test campaigns carried out during the certification activities of the AW609 aircraft.

Further validation of the previous tools using a scaled version of the advanced blade design was carried out thanks to the experimental data from the Clean Sky 2 ATTILA project (Ref. 12).

ATTILA (Advanced Testbed for TILtrotor Aeroelastics) project, involved wind tunnel testing of a semi-span model of a tiltrotor. This testing was conducted to support the development of the Next Generation Civil Tiltrotor (NGCTR) technology demonstrator. The wind tunnel model was designed to target the main dynamic properties of the tiltrotor and was tested to study whirl flutter. The testing was carried out at the F1 Low Speed Pressurized Wind Tunnel at ONERA's Le Fauga-Mauzac Center.

Attila test campaign key objectives can be summarized as:

- Whirl-flutter testing: This dynamic aeroelastic instability—involving coupled motion of the rotor, pylon, and wing—is a primary speed-limiting factor for tiltrotors. ATTILA provides critical experimental data to validate predictive design tools;
- Aeroelastic scaling: Unlike conventionally scaled models, ATTILA is both geometrically and dynamically (mass and stiffness) scaled to emulate real-world structural behavior at reduced size.
- Advanced instrumentation: Utilizes fiber-optic strain sensors and contactless rotating power/data transfer systems to enable real-time modal damping and whirl-flutter monitoring.

Led by NLR with partners DLR, DNW, Politecnico di Milano, and SME Technobis, the team conducted comprehensive design reviews, FEA/MBD structural modeling, and ground vibration tests (GVT) prior to wind tunnel entry. The ATTILA model underwent its primary flutter test in DNW’s 6×6 m low-speed wind tunnel in late 2023, with structural response monitored by DLR’s Göttingen team and supported by Leonardo and Italian teams.

Figure 12– ATTILA model during its primary flutter test in DNW’s 6×6 m low-speed wind tunnel

5. ENHANCED BLADE STRUCTURAL ARCHITECTURE AND VALIDATION CAMPAIGNS

The structural architecture of the RGF3 blade was conceived to meet the demanding operational and certification requirements of tiltrotor flight, which combines the high dynamic loads of helicopter mode with the aerodynamic complexity of fixed-wing cruise. As such, the RGF3 blade represents a significant engineering achievement in balancing structural strength, fatigue resistance, weight control, and manufacturability.

At the core of the blade is a D-shaped spar constructed from carbon/epoxy and glass/epoxy composites. This spar serves as the primary load-carrying structure and is foam-filled to ensure dimensional stability and consistent stiffness. The spar transitions into a hollow circular cuff at the root, enabling attachment to the rotor yoke via two discrete points: one for transferring centrifugal loads and one for shear. This dual-interface configuration distributes loads efficiently and enhances the blade's dynamic behavior.

The trailing edge of the blade is constructed using predominantly glass fiber composite skins supported by a Kevlar honeycomb core. This lightweight and damage-tolerant structure is co-cured with a lag stiffener and diffuser plies, which help distribute loads from the trailing edge into the spar. To improve robustness, diffuser carbon plies are oriented at ±30° at the root end, where structural stresses are highest.

A suite of internal weights—both fixed and adjustable—are embedded along the blade span to tune its dynamic and static balance. Anti-node and tip masses are used to suppress flutter and vibration, while strategically located weight pots at 65% and 86.5% of the radius enable fine-tuning for balance and inertia matching. These elements ensure compliance with aeroelastic stability margins and support interchangeability with existing rotor systems.

Material selection was governed by the need for high-temperature resistance and long-term durability. The blade uses 8552/AS4 carbon fiber pre-pregs with a 175°C cure for the spar and skins, ensuring structural integrity even in the presence of embedded heating elements for anti-icing. Adhesives such as FM300-2 and Loctite EA9309 were qualified through multi-batch programs under various thermal and moisture conditions, including accelerated aging protocols simulating 25 years of service exposure.

The pitch horn, a forged aluminum component, is treated with shot peening, anodization, and chromic acid conversion to ensure fatigue resistance and corrosion protection. It is bolted onto the spar and connects to the pitch control system, enabling accurate blade angle modulation during operation.

For lightning protection, the blade integrates a copper mesh within the skins, electrically bonded to a segmented erosion shield that includes titanium and electroformed nickel components. This system ensures energy dissipation in strike events and protects both the blade structure and internal systems.

The composite manufacturing process uses a matched metal tool to mold the spar, with careful ply layup and consolidation over a five-part NC-machined foam core. The trailing edge and leading edge assemblies are bonded in a reverse-assembly method, followed by trimming, drilling, and installation of balancing components. Final steps include painting, static balancing, and pitch horn installation.

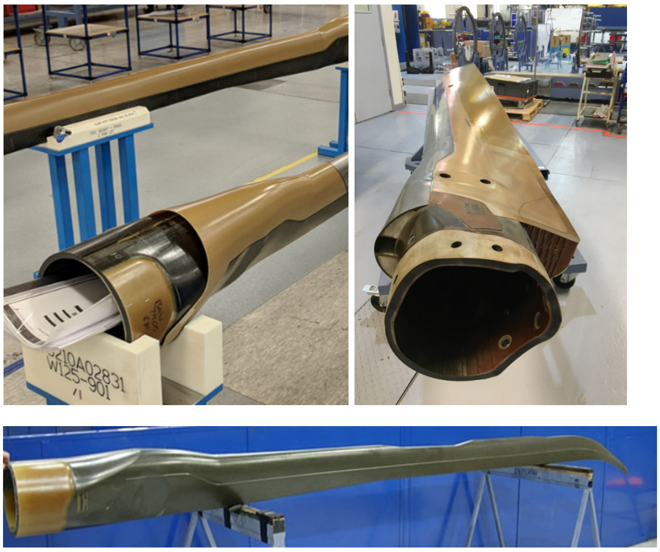

Figure 13 – D-shape foam filled spar that transitions into a hollow circular cuff for coupling to the rotor yoke

In essence, the RGF3 blade's structural and material architecture combines innovation with practicality. It supports high-performance flight while minimizing weight and cost, and its modular construction ensures both ease of production and field serviceability—hallmarks of a mature, certifiable rotor system.

5.1. Manufacturing Process and Quality Assurance

The manufacturing process of the RGF3 blade is designed to meet the dual objectives of high structural performance and industrial scalability. Leveraging modern composite technologies and lean production methodologies, Leonardo Helicopters has established a repeatable and cost-effective fabrication process that supports both prototyping and potential serial production.

The blade fabrication begins with the formation of the D-shaped spar, which is the main structural component. This spar is manufactured using a matched metal tool in which carbon and glass fiber pre-preg plies are laid up over a five-part NC-machined foam core. A pre-cured shim is inserted to prevent ply pinching, and the foam is retained inside the spar except at the root. The layup is vacuum bagged and cured in an autoclave at 175°C to ensure full consolidation and dimensional stability.

The trailing edge assembly is produced in a separate operation. It includes pre-cured glass fiber skins, a Kevlar honeycomb core, and a bonded lag stiffener. Carbon diffuser plies are added at the root to enhance load transfer. Once the trailing edge is prepared, it is bonded to the spar using high-temperature epoxy adhesive under vacuum conditions, again cured in an autoclave.

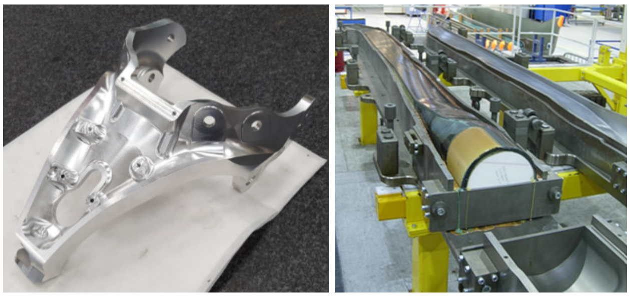

Figure 14– RGF3 forged aluminum pitch horn (left); RGF3 spar production (right)

The leading edge subassembly is then installed. It includes the erosion shield (comprising titanium and electroformed nickel elements), lightning strike mesh, and the dual-layer heater mat system for ice protection. These components are integrated with precision to avoid damage to electrical elements during curing. The entire leading edge is bonded under vacuum at elevated temperature to ensure full mechanical and electrical integrity.

Following structural bonding, the blade enters the machining phase. Trim operations define the blade's final profile, while CNC drilling prepares interfaces for pitch horn installation and weight pot placement. The blade's root profile is also machined to achieve compatibility with the rotor hub. At this stage, anti-node and tip masses, static and dynamic balance weights, and internal bushings are installed.

Quality assurance is embedded at every step of the process. In-process inspections are performed using non-destructive techniques (NDI), such as ultrasonic testing, to detect delamination or voids. Each blade undergoes dimensional checks using coordinate measuring machines (CMMs) to verify geometric compliance. Additionally, all bondlines and embedded systems are visually and electrically inspected before and after cure cycles.

Final steps include surface finishing and painting, followed by a comprehensive static balancing process. The pitch horn—machined from a forged aluminum alloy and treated for corrosion resistance—is bolted onto the root, completing the blade assembly.

To ensure production readiness, Leonardo conducted several pre-qualification builds and manufacturing trials. These efforts confirmed that the RGF3 blade can be fabricated consistently with high yield, minimal rework, and tight process control. The use of modular subassemblies and reverse-assembly methodology further supports parallel processing and reduces lead time.

In summary, the RGF3 blade's manufacturing process blends high-precision composite fabrication with rigorous quality assurance protocols. This integrated approach enables Leonardo to produce blades that meet stringent performance standards while maintaining industrial efficiency, paving the way for future scalability and commercial application.

5.2. Ice Protection System(s) development and testing

The RGF3 blade integrates an advanced ice protection solution developed in collaboration with Collins Aerospace to ensure safe operation in known and potential icing environments. These systems are designed to meet civil certification standards for both anti-ice and de-ice performance while maintaining structural compatibility and manufacturability. Fully validated in dedicated Ice Wind Tunnel (IWT) campaigns, these systems represent a critical component of the RGF3 blade's all-weather operational capability.

The ice protection system which equips the RGF3 blade, consists of a 'dual-redundant' electro-thermal heater mat embedded within the leading edge of the blade. The dual redundant layers are referred to Primary and Secondary system. The Secondary system is called into operation in case of a failure of the Primary one, and it is designed to guarantee the evacuation of the aircraft from the icing environment.

Both system (primary and secondary) are engineered with two independent sub-system—one for anti-icing (continuous operation to prevent accretion) and another for de-icing (intermittent operation to shed ice buildup). Each layer is electrically isolated to ensure functionality in the event of single-point failures.

The heater mat includes spanwise and chordwise zoning, enabling tailored heating intensity along the blade. The Primary system is composed by 8 Electro-thermal De-iced Zones in addition to an Anti-iced (primary) Parting Strip; De-ice sections 1-4 are divided into 2 zones, separated by anti-ice section at the leading edge of the blade airfoils. The anti-ice system is present though just in the last 50% of the rotor blade span going towards the tip to avoid shedding phenomena which can cause impingement with the fuselage cabin. Outboard regions, in fact, are more susceptible to ice accretion, and therefore receive concentrated heat through serpentine and ribbon layouts embedded in ±45° woven glass carriers. Roughly the primary de-icing heat elements span from 15 to 25% of the airfoil chord both along the upper and lower blade surface. The anti-ice heat elements (primary) span roughly up to 4% of the airfoil chord both along the upper and lower blade surface.

The Secondary (or backup) system is composed by 4 Electro-thermal De-iced Zones in addition to an Anti-iced (primary) Parting Strip; being a backup system its dimensions are smaller in chord with respect to the Primary one, but it still extends along the overall radius of the blade.

This system was tested across over 220 points in the Iowa State IWT campaign at Collins facility, covering a range of airspeeds, temperatures, and liquid water contents (LWCs). The test matrix included simulated failures of the primary layer to validate the redundancy logic and thermal margins. Results confirmed the system's ability to maintain ice-free operation across both helicopter and airplane mode envelopes, without exceeding allowable structural temperatures.

In parallel to the heater mat development with Collins (main solution selected for the ice protection of the RGF3 blade), as part of the Clean Sky 2 "NoIce Rotor" initiative (Ref. 13), Leonardo partnered with Villinger GmbH to develop a second, innovative heater system—an ultra-reliable full-face heater blanket. This solution provides heating coverage across the entire leading edge surface and is designed to perform under high-strain and vibration conditions typical of tiltrotor blades. The Villinger blanket uses high-strength conductors embedded in a durable polymer substrate. Both anti-ice and de-ice functions are provided through zoned activation strategies. The system includes embedded sensors and is optimized for minimal thickness and weight impact, preserving blade aerodynamics and mass distribution.

Environmental performance of the blanket was verified through IWT tests in Vienna (RTA facility), confirming its efficacy at extreme conditions (−30°C at 115 knots and −20°C at 155 knots). Fatigue testing of coupons and full-span samples ensured long-term reliability and electrical continuity under dynamic loads.

Both ice protection systems described in this section were developed with full integration into the RGF3 blade's manufacturing workflow and structural design. Heating elements are embedded early in the bonding sequence and protected by the erosion shield and outer composite skins. Electrical routing and grounding were carefully engineered to ensure EMI shielding and system redundancy.

The availability of two distinct systems—each independently validated and compatible with the blade architecture—enhances Leonardo's flexibility for future platform integration. The dual-solution strategy also supports risk mitigation and cross-validation during certification testing.

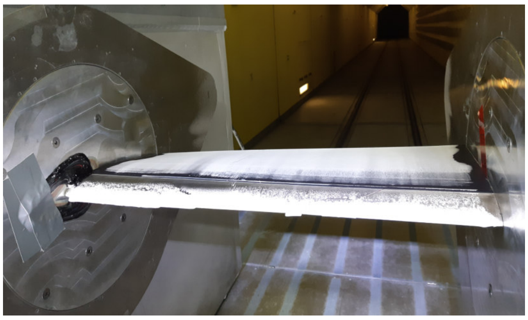

Figure 15– Villinger heater mat / RGF3 Outboard Specimen - Functional Primary & secondary systems, embedded temperature sensors. Run MS-#8 Ice Accretion (LWC=0.94 g/m3, MVD=35 µm, OAT=-27.6°C, Speed=115 knots)

Figure 45 – Run RT-#7 Ice Accretion (LWC=0.68 g/m^3, MVD=38 µm, OAT=-18.3°C, Speed=155 knots)

Figure 16 - Villinger heater mat / RGF3 Inboard Specimen - Functional Primary & secondary systems, embedded temperature sensors

In conclusion, the RGF3 blade's ice protection systems exemplify a robust, multi-layered approach to operational safety. By incorporating advanced heating technologies with validated aerodynamic and structural integration, Leonardo has equipped the blade for reliable all-weather tiltrotor operations across a broad mission envelope.

5.3. Structural testing

To ensure the RGF3 blade's airworthiness and performance prior to integration into the NGCTR-TD aircraft, Leonardo Helicopters executed a rigorous series of validation campaigns. These efforts spanned structural, environmental, and impact testing domains, each aligned with civil certification protocols and internal safety standards. The validation strategy followed a 'testing pyramid' philosophy—beginning with material coupons and progressing through subcomponents to full-scale blade assemblies.

Full-scale test articles were subjected to both static and fatigue load regimes in high-temperature dry (HTD) and room-temperature dry (RTD) conditions. Structural validation of the RGF3 blade focused on two primary sections of the blade: Root/Transition and mid-span (Central) region; a future test is planned on the Tip (outboard) portion of the blade in 2026. In relation to the Root/Transition region of the blade, several high-frequency (HF) and low-frequency (LF) fatigue blocks were carried out, separated roughly every 25,000HF and 2-5000 LF cycles by static tests to Proof/Factored Limit (HTD) loads. Testing to grant first flight clearance was then concluded by applying Factored Ultime loads (HTD). Roughly the same approach was taken in testing the Central segment of the blade. In terms of Structural Coupons, both Spar sidewalls (tensile/compressive tests) and CF lug elements were tested. All tests were conducted under RTD or HTD conditions, without induced damage, and no failures were observed up to test limits. No failures or delaminations were observed, and measured strains remained within allowable limits with substantial safety margins. The data closely correlated with predictions from Leonardo's BSAP (LHD proprietary structural tool) analytical models, confirming design fidelity and enabling flight clearance with a conservative life limit.

The Enhanced Blade demonstrated therefore adequate structural integrity for NGCTR-TD Phase 1A flight. Testing exceeded required margins without failures, and analytical predictions were validated through experimental correlation. The results support blade clearance for experimental flight activity with a conservative 3-year life limit due to unaged test coupons.

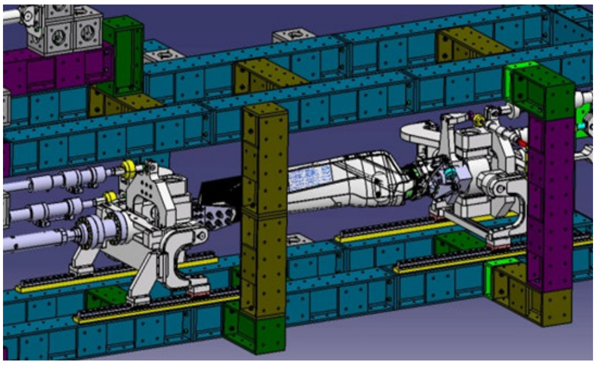
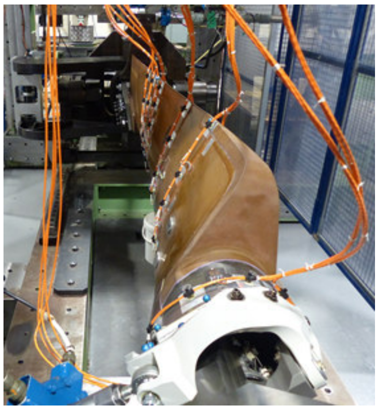

Figure 17 – Test Rig developed for blade structural testing (left). Blade Root specimen under fatigue testing (right)

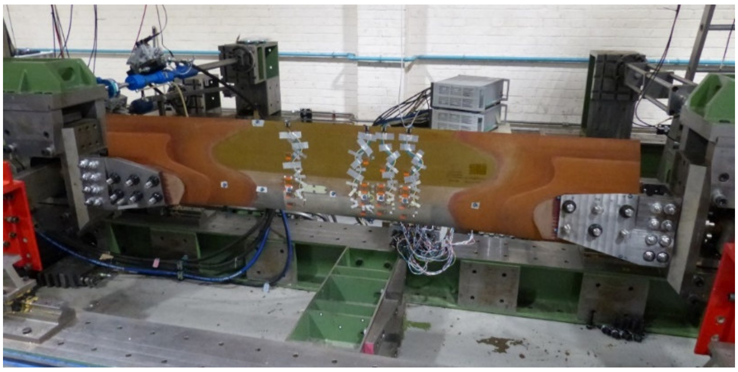
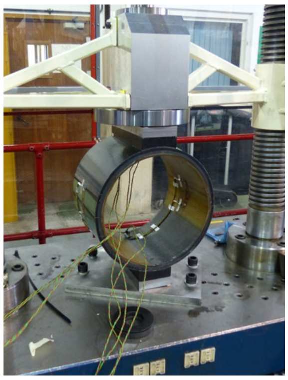

Figure 18 - Enhanced Blade Central Test Specimen (left); Compression testing of the hollow circular root cuff (right)

5.4. Bird-Strike Testing and Modeling

Bird-strike resilience is a critical certification requirement for tiltrotor aircraft, particularly due to their wide range of operating speeds and altitudes. In both helicopter and airplane modes, rotor blades are exposed to the risk of high-energy impacts that could compromise structural integrity and flight safety. To address this challenge, Leonardo Helicopters conducted a dedicated bird-strike test and modeling campaign as part of the RGF3 blade validation process.

The campaign was executed in partnership with Politecnico di Milano and was designed to serve dual objectives: empirically validate the RGF3 blade's response to bird-strike events and develop predictive simulation tools for future design assessments. This combined approach enabled a high-fidelity understanding of impact dynamics and structural tolerances.

Test Setup and Scenarios: Three physical bird-strike tests were performed using gel-based surrogate bird projectiles to simulate real-world impact conditions. The test articles consisted of blade tip specimens fabricated with representative materials, geometries, and internal architectures matching the final RGF3 design. Impact conditions included:

- Velocities ranging from 187 to 216 m/s

- Impact angles from −6.9° to −36° relative to the blade chord
- Projectile masses from 925 g to 1834 g

Test locations were focused on the outboard blade region (STN 3850), where tip speed and energy transfer are most severe. Each impact was filmed at high frame rates, and post-impact evaluations were conducted using non-destructive inspection (NDI) techniques.

Results and Observations: The first two tests showed no visible or detectable damage. After the third and most severe impact, localized debonding of the trailing edge skin from the honeycomb core was observed, along with crush deformation of the honeycomb itself. No structural failure of the spar or load-bearing elements occurred, and damage was confined to secondary structures. These results confirmed that the RGF3 blade design provides a robust safety margin even under worst-case impact conditions.

Numerical Modeling: Parallel to the physical testing, Politecnico di Milano developed a high-fidelity LS-DYNA finite element model of the RGF3 blade tip. Material parameters were calibrated through earlier flat-plate coupon tests. In addition, LHD developed and worked on the same topic by using Abaqus/Explicit environment using the Smoothed-Particle Hydrodynamics (SPH) technique. Both FE models was capable of simulating:

- Progressive fiber and matrix failure
- Delamination and skin/core debonding
- Honeycomb crush behavior

The physical test results were used to validate the model, particularly the extent and type of damage observed in the third test. The correlation confirmed the model's ability to predict damage initiation and propagation across a range of impact scenarios.

Application and Certification Relevance: The validated numerical model is now being used to explore a broader matrix of bird-strike conditions that would be impractical to replicate physically. This includes variations in bird mass, angle of impact, blade pitch, and rotor speed. These simulations will inform the final certification bird-strike envelope and guide protective design adjustments if needed. In conclusion, the RGF3 blade's bird-strike campaign has demonstrated strong impact resilience backed by experimental data and supported by advanced numerical modeling. This combined methodology ensures that the blade meets regulatory safety margins while reducing the need for exhaustive physical testing in future development cycles.

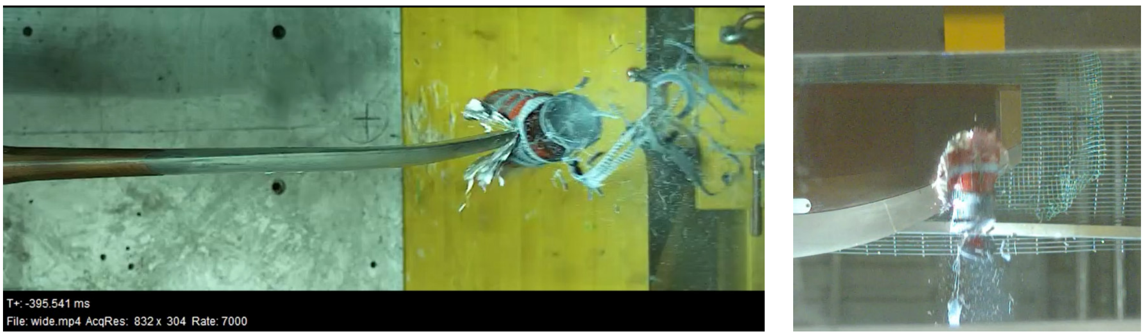

Figure 19 – Physical bird-strike tests were performed using gel-based surrogate bird projectiles (POLIMI test facility)

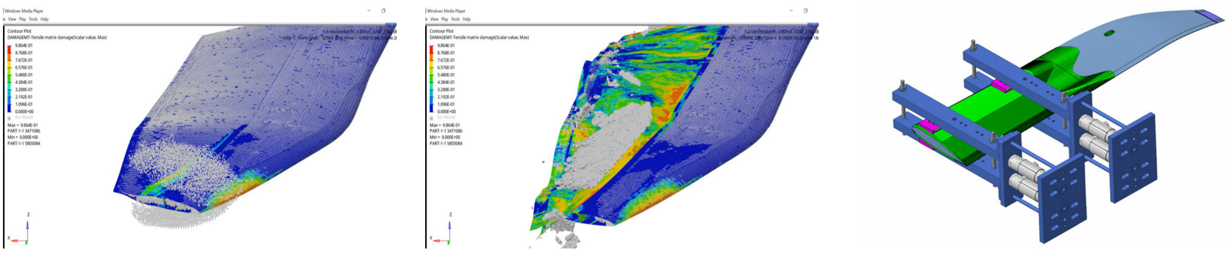

Figure 20 – Modelling and simulation activity of birdstrike blade impact (left, center). Preliminary test rig design for birdstrike experimental activity to support numerical methods predictions (right)

6. GROUND RUN AND FLIGHT TEST READINESS

On 26 July 2024, Leonardo Helicopters successfully conducted the first ground run of its Next Generation Civil Tiltrotor (NGCTR) Technology Demonstrator at its Cascina Costa facility in Italy. This event marked the first time the aircraft's proprotor systems were powered up and exercised, verifying key mechanical systems including:

- Rotor actuation and transmission functionality;
- System responsiveness and coordination;
- Ground safety protocols for engine–rotor interaction.

The test validated the integrated performance of the new rotor system, split gearbox, and fly-by-wire flight control system, confirming proper alignment and dynamic response under powered conditions. The test was a major milestone in the NGCTR's development, paving the way for upcoming engine runs and eventual flight testing.

The ground run followed the completion of aircraft assembly in June 2024, and it was a prerequisite to initiating the aircraft's 200-hour flight test campaign

The successful ground run on 26 July 2024 marked a pivotal milestone for NGCTR — transitioning it from assembly to active testing. With first flight moving into 2025, Leonardo is positioning NGCTR as a potentially game-changing civil tiltrotor: high-speed, long-range, low-emission VTOL transport.

The next phase of the programme involves intensive testing in the coming months, with the aim of performing the first flight by the end of Q3 2025 and then accumulating 200 flight hours to expand operational capabilities in helicopter and aircraft modes.

7. CONCLUDING REMARKS

The development of the RGF3 rotor blade marks a significant milestone in the evolution of tiltrotor technology, offering a harmonized blend of aerodynamic efficiency, structural innovation, and operational adaptability. Designed and validated through a multi-year effort under the Clean Sky 2 initiative and Leonardo's parallel R&D programs, the RGF3 blade embodies the vision for a next-generation rotor system capable of elevating the performance of civil tiltrotor platforms such as the NGCTR-TD.

From its inception, the RGF3 blade was conceived to address the shortcomings of legacy systems while introducing advanced features to meet modern mission demands. These include the proprietary AMDX airfoil family, highly swept and anhedral tip geometries, non-linear twist distributions, and fully integrated ice protection solutions. Each design choice was informed by an iterative optimization process that combined computational modeling with wind tunnel and structural validation.

Structurally, the RGF3 blade introduces a robust yet lightweight architecture based on a foam-filled composite spar, advanced trailing edge materials, and embedded weight and heater systems. These features ensure compliance with the demanding dynamic environment of tiltrotor operations and simplifying certification paths.

Extensive validation campaigns—including structural testing, bird-strike trials, wind tunnel evaluations, and high-fidelity CFD simulations—confirmed the blade's aerodynamic and mechanical performance. The RGF3 demonstrated improvements in hover thrust, cruise propeller efficiency, fuel economy, and autorotation capability, all while reducing noise, vibration, and maintenance complexity.

The blade's manufacturability has also been proven, with a modular, reverse-assembly process enabling high repeatability, reduced costs, and alignment with industrial production standards. This positions the RGF3 not only as a prototype achievement but also as a scalable solution for future serial applications.

From a mission performance perspective, the RGF3 blade enhances aircraft capabilities across the full operational envelope. Whether in high-altitude rescue missions, high-speed transport, or challenging maritime operations, the blade delivers measurable gains in payload, range, endurance, and safety. These attributes directly support the NGCTR program's objective to create a commercially viable, low-emission, and highly flexible tiltrotor platform.

Looking ahead, the RGF3 blade will serve as a foundation for future rotor system developments, informing designs not only for advanced tiltrotors but potentially for high-speed helicopters and next-generation VTOL aircraft. The success of the RGF3 program underscores Leonardo's commitment to innovation, sustainability, and leadership in the evolving rotorcraft landscape.

In conclusion, the RGF3 rotor blade exemplifies what is possible when advanced computational tools, rigorous testing, and a clear design vision converge. As the NGCTR-TD prepares for flight and eventual certification pathways mature, the RGF3 blade stands ready to define the next era of tiltrotor excellence.

Author contact:

Andrea D'Andrea, andrea.dandrea01@leonardo.com

8. ACKNOWLEDGMENTS

The author would like to thank all Leonardo Helicopter Division colleagues which were involved in this development program (Rotor Systems, Aircraft System Integration, Manufacturing, Operations, Structural Testing, Material Labs and Program Office), the Clean Sky 2 Joint Undertaking, and our Clean Sky 2 partners who made this work possible.

9. REFERENCES

1. Vertiflight, The Vertical Flight Society, Dec 2017, “The Leonardo Next Generation Civil Tiltrotor”, pages 36-41.
2. A., Massaro, D’Andrea, A., Benini, E., “Multiobjective-Multipoint Rotor Blade Optimization in Forward Flight Conditions Using Surrogate-Assisted Memetic Algorithms”, 37th European Rotorcraft Forum Proceedings, Gallarate, Italy, Sept. 2011.
3. D’Andrea, A., “Development of a Multi-Processor Unstructured Panel Code Coupled with a CVC-Free Wake Vortex Model for Advanced Analyses of Rotorcrafts and Tiltrotors”, American Helicopter Society 64th Annual Forum Proceedings, Montréal, Canada, April 2008.
4. D’Andrea, A., “Enhanced Numerical Simulations of Helicopter Landing Maneuvers in Brownout Conditions”, AHS Annual Forum Proceedings, May 11-13, 2010, Phoenix Convention Center, Phoenix, AZ.
5. D’Andrea, A., “Exploitation of Active Controls and Morphing Technologies to Enhance Rotor Aerodynamic Performance in Hover Conditions”, AHS Specialist’s Conference on Aeromechanics Proceedings, January 20-22, 2010, Fisherman’s Wharf, San Francisco, California.
6. D’Andrea, A., “Numerical Analysis of Advanced-Innovative Tiltrotor Configurations”, 34th European Rotorcraft Forum Proceedings, September 16–19, 2008, Liverpool, UK.
7. S. Melone, D’Andrea, “Helicopter Main Rotor - Tail Rotor Interactional Aerodynamics and Related Effects on the On-Ground Noise Footprint”, 37th European Rotorcraft Forum Proceedings, Gallarate, Italy, Sept. 2011.
8. Jimenéz Garcia, A. and Barakos, G.N. ‘Accurate predictions of rotor hover performance at low and high disc loadings. Journal of Aircraft, 55(1), 2018, pp. 89-110.
9. Johnson W., “Technology drivers in the development of CAMRAD II”, Proceedings of the American Helicopter Society Aeromechanics Specialists Conference, San Francisco, California, 1994.
10. Masarati P., Muscarello V., Quaranta G., “Linearized aeroservoelastic analysis of rotary-wing aircraft”, In proceedings of the 36th European Rotorcraft Forum, Paris, France, September 2010.
11. Chengjian He (2004) Flightlab Theory Manual. Advanced Rotorcraft Technology, Inc.
12. https://www.attila-project.eu/
13. https://www.clean-aviation.eu/sites/default/files/2021-10/CLEAN_SKY_Article_NO-ICE-ROTOR.pdf.