“CLEAN SKY 2”: EXPLORING NEW ROTORCRAFT HIGH SPEED CONFIGURATIONS

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ABSTRACT

This paper presents a multi-disciplinary overview description of a high speed compound helicopter configuration which is under development at Airbus Helicopters in cooperation with several European partners in the frame of the Clean Sky 2 research program. Clean Sky 2 is a European research program aiming to improve the efficiency of aeronautic transport. The specific project within Clean Sky 2, led by Airbus Helicopters, deals with the development and testing of an innovative rotorcraft demonstrator (RACER) which is developed for its high-speed capability particularly at the benefit of assistance to citizens (more efficiency for health & safety mission, door to doors transport…). The aim herein is to demonstrate the viability of a commercial aircraft on the basis of the concept validated in the recent past by the Airbus Helicopters X^3 demonstrator. The high speed compound rotorcraft formula aims outstanding operational and economical enhancements in comparison to conventional helicopters exploiting the advantages of high-range, high-speed characteristics in combination with hovering capabilities whilst ensuring a high degree of safety and environmental friendliness.

The paper mainly provides an overview of the global architecture of the Clean Sky 2 high speed vehicle in relation to its structure-mechanic, aerodynamic and aeromechanic performance. The paper first gives a brief introduction to the targets and organization of the Clean Sky 2 project which is followed by an overall description of the latest architectural characteristics of the high speed compound helicopter focusing on the new joined wing concept especially in comparison to mono-wing configurations. The main evolutions of the aircraft configuration and their associated improvements are highlighted. These improvements mainly refer, among other aspects, to enhanced safety, systems integration and definition (especially landing gear), payload ratio, aerodynamic performance (especially downwash), structure-mechanical characteristics as well as structural static and dynamic stiffness (especially in interaction with the dynamic system).

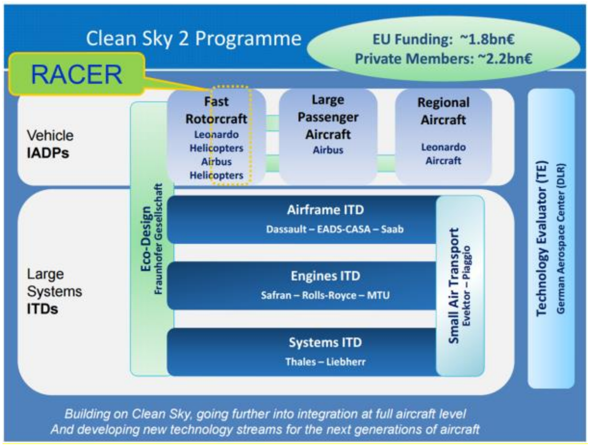
The chosen detailed architecture is a result of the most efficient overall compromise on vehicle level regarding ambitious targets in terms of operational, tactical, economic, and safety aspects. The evolutionary configuration is underlined by a modern and unique layout and style.

1. INTRODUCTION

1.1 Introduction to the European Clean Sky 2 Program

The Demonstrator project RACER is part (Work Package 2) of the Innovative Aircraft Demonstrator Platform (IADP) Fast RotorCraft of the European Research Program Clean Sky 2 (Fig. 1). The aim of Fast Rotorcraft Platform is to develop new VTOL formula in order to fill the mobility gap between conventional helicopters and airplanes (Fig. 2).

This type of aircraft will insure more efficient emergency services (Emergency medical services - EMS, Search and Rescue -SAR…) and improved citizen mobility by offering faster gate to gate passenger transport.



Building on Clean Sky, going further into integration at full aircraft level
And developing new technology streams for the next generations of aircraft

Fig. 1: Clean Sky 2 Programme organisation

Presented at the 43rd European Rotorcraft Forum, Milan, Italy, September 12–15, 2017.

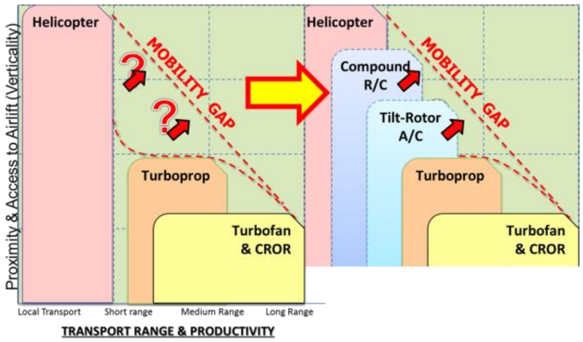


Fig. 2: Mobility gap between helicopters and airplanes to be filled by fast rotorcraft formulas

This contributes to the safety and wellbeing of European citizen's. The target of the project is also to reduce the environmental impact of this type of rotorcraft: fuel consumption/CO2 emission reduction, noise foot print, eco design.

This project is developed under the leadership of Airbus Helicopters Group within a large European partnership.

The team includes 8 Core-partners (major role in the project) and 18 Partners (Fig. 3). These partners have been selected through open calls managed by the European Commission on the basis of requirements prepared by Airbus Helicopters.

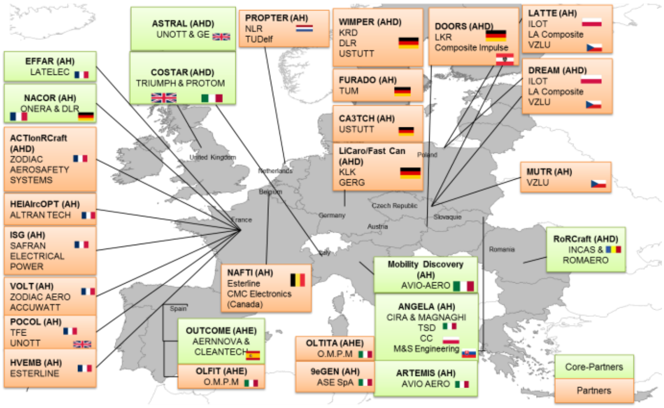


Fig. 3: RACER demonstrator partnership

This large partnership gives opportunities to a large number of European companies (including SME's) or institutes to participate to this innovative project and to develop until TRL 6 (flight tests) new technologies contributing to the performance improvement of the concept. Innovative tools have been implemented between the partners as "Extended Enterprise" in order to insure the best efficient collaborative work.

1.2 Introduction to High Speed Rotorcraft

1.2.1 Historical Review

Conventional helicopters show excellent hover capabilities but suffer from major limitations in terms of horizontal flight speed. These limitations are associated to two aerodynamic phenomena at the main rotor: the retreating blade stall and the maximum blade tip velocity. In general terms, the lift and thrust force capabilities of a helicopter rotor decrease with forward speed.

There have been numerous attempts to combine the efficiency and performance of fixed-wing aircrafts in forward flight and the advantageous hover and vertical take-off capabilities of helicopters. The compound helicopters and the convertiplanes are basically the most promising concepts aiming to overcome the horizontal flight deficiencies of pure helicopters by introducing features of fixed-wing aircrafts. However, all concepts represent a compromise between both aircraft types which has always to be conveniently adapted to the planned aircraft´s mission profile. Two well-known examples of convertiplanes are the V-22 Osprey and the AW 609.

Compound helicopters are characterized by a lift compounding, a thrust compounding or by a combination of both and basically aim to off-load the rotor from its simultaneous lifting and propulsive duties to allow for higher forward speeds [8]. A lift compounding entails adding wings to a pure helicopter hence enabling to increase the load factor of the aircraft and to reach a higher manoeuvrability. This improves the efficiency of the helicopter at moderately high speed but at the expense of reduced efficiencies at lower forward speeds and in hover. One example is the Sikorsky S-67. A thrust-compound however implies the addition of auxiliary propulsion devices. This has been typically accomplished either by means of a single or a pair of propellers being driven by transmissions powered by the main turboshaft engines or by the use of additional engines. Examples are the Sikorsky S-69, the VFW H3 and the Gyrodyne GCA-2A. The S-97 represents a modern thrust-compound helicopter featuring coaxial main rotors in combination with a single rear mounted pusher propeller. A thrust-compound has been deemed more effective in comparison to a pure lift-compound configuration.

A more extended configuration of a compound helicopter includes both the addition of wings and propulsion units. The lift during cruise is simultaneously provided by the main rotor – in powered condition or in autorotation modus – and wings. The compound helicopter consequently overcomes the rotor lift limits by means of the wings and the rotor thrust limits by means of the propellers. As a result the benefit of a higher load factor is obtained along with potential for higher speed. The use of a pair of thrust propellers enables a simultaneous torque correction by a compensated pair of forces. An early example of this compound concept is the Fairey Gyrodyne, a recent example is the Airbus Helicopters - X^3 demonstrator.

The propulsion devices of compound architectures are typically attached to the fuselage or arranged at the wings or at the aft end of either the tail boom or the fuselage. The attachment of the engines to the fuselage is only feasible if using turbojets (Bell Model 533, Kaman UH-2, Lockheed XH-51A). Despite the advantage of having clean wings, this arrangement does not allow for anti-torque capabilities, hence still requiring an additional tail rotor. The same applies for configurations with a single main rotor and a tail-boom mounted pusher propeller (AH-56A). Propellers are typically arranged on the wings, either somewhere between the wing tip and the fuselage (Fairey Rotodyne) or at the wing tip (Fairey Jet Gyrodyne, AH-X^3).

A large variety of compound architectures has been explored and some of them have been developed to a certain level of maturity but never reaching serial production yet.

1.2.2 X^3 compound configuration

As defined in [10], the X^3 configuration is characterized by:

- A single wing supporting two tractor propellers (or lateral rotors) providing the control of propulsion and yaw axis. This wing was tested up to 60% of lift.
- A permanent transmission driving the main rotor and the two lateral rotors with a constant ratio. Each half-wing contains a shaft linking the lateral rotor gearboxes to the lateral outputs of the main gearbox.
- The H-tail provides improved yaw efficiency. The twin fin configuration is much less subject to the rotor head and fuselage wake than a central fin imposed by the presence of a tail rotor and its transmission.

Fig. 4: X^3 demonstrator – Flight in Istres Flight Test Centre area

2. THE “RACER” CONFIGURATION

2.1 Basic Architecture and Innovation

The RACER demonstrator will be a medium class rotorcraft with a cruise speed exceeding 220 kt. The basic architecture is capitalizing the experience gained by the X^3 demonstrator. It keeps the principle of a compound rotorcraft including a wing and propellers (or lateral rotors). The main innovative aspects are at the level of the general architecture described below and the integration of each sub-systems. New technologies are implemented in order to contribute to the overall efficiency as advanced composite structural components, optimised transmission architecture and high voltage DC generation. The demonstrator sizing is optimized to perform the targeted missions, particularly EMS, SAR and passenger transport.

The benefit for this type of mission is very significant and can be illustrated by the following examples.

A major point for the success of Emergency and rescue operations is to be able to reach the persons in difficulty within one hour; it is called the “Golden hour”. By increasing the cruise speed by 50%, the accessible area within one hour is doubled. Beyond the fact that a lot of persons in difficulty will be rescued quicker, a best coverage of a region is insured with a lower foot print (less bases). In addition, for a given distance, more missions can be achieved during the day. It contributes to the economic efficiency of the formula.

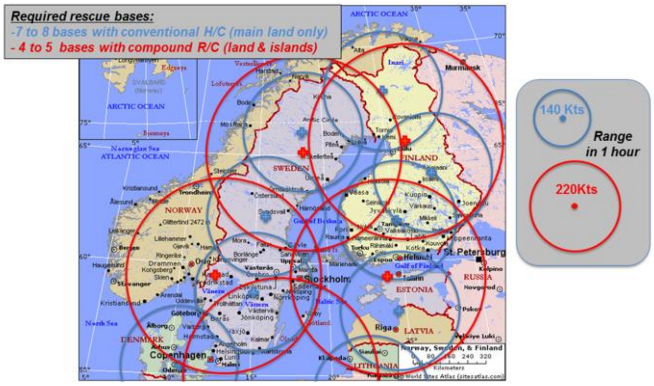


Fig. 5: Example of coverage within the “Golden Hour”

For door to door passenger transport, the increase of the speed allows to travel in less than one hour between large European urban centres as well between medium size cities with the following benefits in comparison with conventional helicopters:

- Less time on board
- Avoid need for several transportation means for a medium distance
- Increased comfort
- Increase of productivity (Payload x Range / Flight hours) higher than cost increase

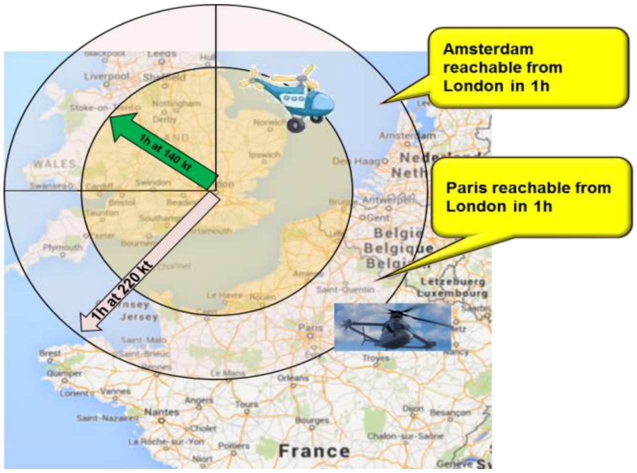


Fig. 6: Door to door connection within 1 hour

Fig. 7: The “RACER”

2.2 The Wing Architecture

Early in the beginning of the project during the conceptual phase, a joined wing configuration was suggested – previously conceived at Airbus Helicopters Germany for future high speed compound helicopters [1],[2], – as a potential alternative against a typical cantilevered shoulder wing configuration as used for the X^3 program. The suggestion originated from an overall global view of the aircraft with a pronounced emphasis on improved weight efficiency, architectural simplicity and operational safety. The new wing arrangement is defined as a staggered bi-plane configuration with an upper and a lower straight wing at each side of the helicopter, both being interconnected at their outermost tips, hence essentially forming a triangular framework in a front and top view (Fig. 8). The lateral rotor is allocated in pusher configuration at the wing interconnection region behind the trailing edges, the lateral rotor disc hence operating behind the cabin and boarding area and the lateral rotor driving shaft being housed within the upper wing. Both wings show opposed dihedral and sweep angles with a positive stagger arrangement at their roots.

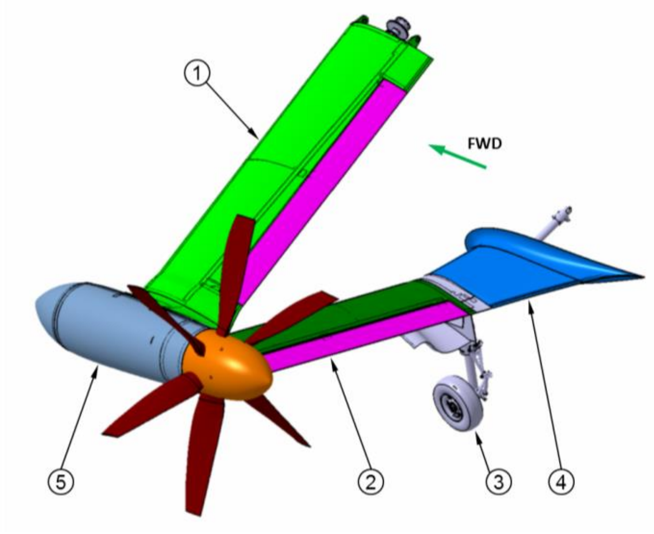


Fig. 8: Joined wing. 1,2,4: upper wing, lower wing and stub wing resp. 3: main landing gear. 5: lateral gear box nacelle.

In comparison to a mono-wing arrangement with a similar total wing lift, the joined wing is characterized by a considerably larger stiffness in vertical direction (flapping direction), but by a lesser bending stiffness in longitudinal direction (feathering direction), which is a result of the wing truss arrangement in an essentially vertical plane in combination with a smaller wing chord. More precisely, the both global principal axes of the trussed braced wing are rather moderately inclined with respect to the global aircraft axis as a result of the wing staggering. In any case, the ratio of the deficient bending stiffness of both concepts (flapping for mono-wing, feathering for joined wing) results to be favourable for the joined wing for similar structural mass (X^3 showed some flapping sensitivities during test campaign). Moreover, the wing root forces and moments are considerably larger in the vertical plane than in the longitudinal plane as a result of larger flight load factors in vertical direction. In view of the requirements of the wing in terms of its maximum angular deflections between its root and tip with respect to the admissible deflections of the shaft couplings, there is a strong demand, especially for the increased wing span, for a large stiffness in an essentially vertical plane. Despite of a loss of torsional stiffness of the single wing box section in contrast to the larger mono-wing wing box section, the torsional stiffness is significantly improved by the wing's interconnection, the differential bending capability of both front and rear spar truss scheme as well as the staggered position of the wings which transforms a portion of the global torsion into wing bending. Consequently, the braced wing was deemed all in all the most promising concept in terms weight efficiency with its outstanding truss characteristic being arranged within the mostly demanded working plane.

The joined wing design is conceived with one upper wing attached at the upper fuselage and a lower wing attached at the lower fuselage region. In view of the overall mechanical arrangement as a simple triangular truss, the wings are mainly subjected to tension and compression loads, with superimposed bending, transverse shear and minor torsion as a result of the corresponding aerodynamic lift, flap actuation and the propeller thrust. The predominant axial loading (tension/compression) of the wings emphasizes the mechanical efficiency of the wings, acting globally as longitudinal members – and locally as beams – within the most severe loading plane. The wings are hence straight to achieve an optimal overall stiffness and structural simplicity as well as to allow housing the drive shaft. A pure overall truss arrangement is, however, not feasible due to the constraints of the lateral gear box housing in combination with aerodynamic and other non-structural limitations. As a consequence, both wing tips are interconnected by keeping some minimum distance to each other (Fig. 9). This introduces indeed some minor parasitic bending on the wings at their outer sections but improves on the other hand the available basis for lateral propeller attachment and its torque reaction.

A cantilevered mono-wing design would require a large wing root thickness with a large chord and a continuation of the wing bending capabilities throughout the upper fuselage deck which translates to a detrimental impact on the compatibility with the main gear box housing. The suggested joined wing on contrary allows for a reduction or an elimination of the bending capability continuity at the wing roots by introducing e.g. simple hinge attachments to the fuselage, hence transferring transverse and longitudinal loads only. This allows for minimizing obstructions within the mechanical deck and a better accessibility to the gear box.

For a conventional helicopter, the lifting load generated by the main rotor acts at the upper fuselage deck and enforces to design strong main frames which transmit the lifting load to the main structural members of the subfloor airframe, where the main payload and fuel masses are allocated. The same applies for a shoulder mono-wing configuration, when a large portion of the lifting loads at maximum manoeuvring load factors are provided by the wings. In contrast, the braced wing configuration transmits a portion of the resultant lifting load directly to the subfloor structure, hence alleviating the loading of both main frames and consequently reducing their structural mass. Similar behaviour is present during a crash scenario where the wing and lateral propeller inertia loads are partially directly transmitted to the lower fuselage in direct contact to the ground.

The use of an upper wing for the envisaged compound helicopter is essential facing the lateral propeller shaft housing. The sweep and anhedral of the upper wing is a function of the position of the main gear box and the lateral rotor and the required clearances to the main rotor and the ground (Fig. 9).

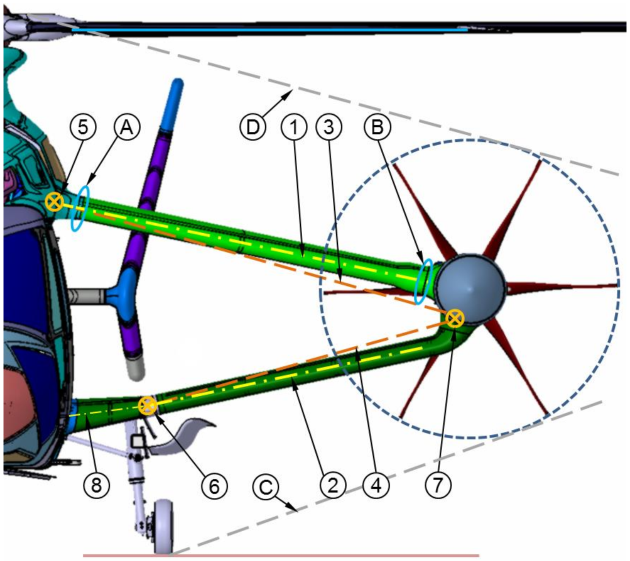


Fig. 9: Joined wing scheme. 1,2,8: upper wing, lower wing and stub wing centroidal axis resp.; 3,4: upper and lower wing action line resp.; 5,6: upper and lower wing root hinge resp.; 7: wing interconnection hinge; A,B: inboard and outboard soft coupling resp.; C,D: clearance threshold lines.

The use of a lower wing leads, beneath said structural advantages for the wing and airframe, to additional advantages in terms of safety, landing gear integration capabilities and aerodynamics. The longitudinal root position of the lower wing is mainly a function of the landing gear position, due to the main landing gear being intended to be at last partially housed within the lower wing. Since the position of the landing gear is aft of the main rotor, the braced wing arrangement results in a staggered configuration with a lower wing positioned clearly aft with respect to the upper wing. As a result, the upper wing and the lower wing show a positive and a negative sweep angle respectively, the bi-plane arrangement hence being staggered within the root regions of the wings and mutually overlapping at their interconnection region.

In the case of the present compound helicopter with two propellers of considerable diameter mounted on wings with enlarged span compared to X^3, there is a crucial need for ground clearance in order to avoid a clash of the propellers to the ground. A basic parameter to influence the ground clearance is the wheel track. Consequently, a mono-wing configuration requires a big, complex and heavy landing gear, with complex and susceptible kinematics with a large landing gear length in combination with either a large cut-out and large storage volume within the main fuselage or a largely protruding sponson. The former severely reduces the airframe's structural efficiency and the fuel storage volume within the fuselage, and the latter adds non-working additional structural mass with a severe negative impact on aerodynamic drag, both alternatives being not efficient for high-speed rotorcrafts. As a result, the use of a lower wing entirely solves the problem associated with the landing gear design, its structural integration and its impact on aerodynamic performance, allowing simultaneously the use of a rather conventional, low-cost and highly robust landing gear. The wheel is then partly housed within the lateral subfloor fuselage (Fig. 11). The result is a structurally simple, weight-efficient, cheap, robust and aerodynamically clean solution for the landing gear integration, which is quite familiar with traditional fixed wing configurations.

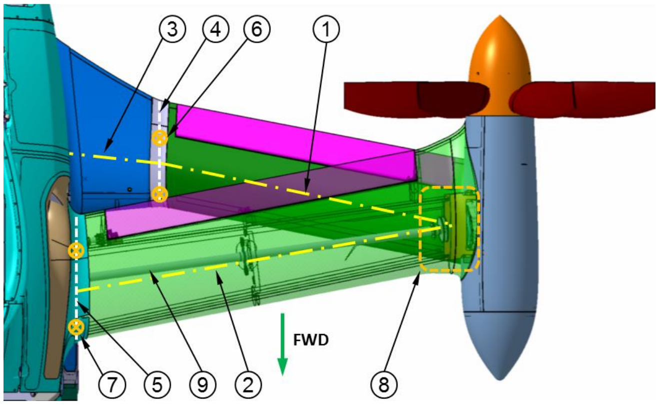


Fig. 10: Braced wing staggering with overlapping wings at their outermost interconnection region (8) and positive stagger at their roots (top view). 1,2,3: centroidal axis of lower, upper and stub wing resp. 4,5: root hinge axis for lower and upper wing resp. 6,7: root joints of lower and upper wing resp. 9: transmission shaft.

A further improvement has been achieved by introducing a polyhedral design of the lower wing planform with an inboard and an outboard wing section with slightly different sweep and dihedral angles, as well as different chord and airfoil thickness [3] (Fig. 9, Fig. 10). The landing gear and the interface between the inboard and the outboard wing sections are allocated at the associated kink of the lower wing (Fig. 11). The inboard wing section is hence designed as a stub-wing which is protruding from and being structural part of the airframe, whilst the outboard portion of the lower wing is part of the removable joined wing unit. This leads to the advantage of directly introducing the landing gear loads to the fixed airframe without any intermediate structural joint, optimally housing the landing gear between the stub wing spars once retracted and furthermore allowing the aircraft “stand on its own feet” with dismounted wings. Moreover, the reduction of the dihedral angle of the lower wing at its root region improves the aerodynamic efficiency of the wing-to-fuselage transition, especially considering the larger airfoil thickness and chord and the large lifting capability of the stub-wing.

In contrast to the X^3 arrangement, the suggested joined wing architecture incorporates lateral propellers in pusher configuration, in order to ensure outstanding characteristics in terms of safety and crash-worthiness. The propeller disc is now allocated behind the cabin and the boarding area including the baggage door. In addition, the lower wing provides for a physical barrier between the boarding area and the rotating lateral propellers. This fact is deemed crucial for hoisting operations, the lower wing serving as barrier in case of an emergency exit avoiding the occupants running into the rotating propellers. For a ditching case, the lower wing acts as additional buoyancy body providing for lateral stability counteracting the capsizing effect. In case of a crash vertical scenario, the lower wing impedes the upper wing braking and flapping towards the cabin. Furthermore, the pusher disc allocation behind the cabin alleviates the acoustic excitation within the cabin compartment improving cabin comfort.

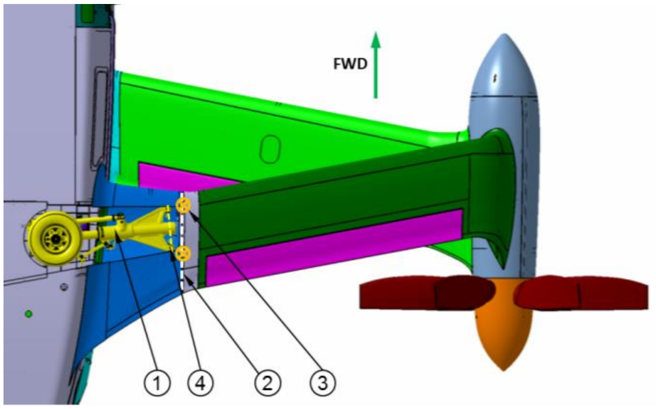


Fig. 11: Integration of the main landing gear (1) within the stub wing box and quarter shell subfloor fuselage (doors not shown). 2: root hinge axis of lower wing. 3: joints at spars. 4: main landing gear hinge line.

Moreover, the joined wing architecture features an inherent hyperstatic characteristic. The loss of one hinged connection of the wings to the fuselage or the entire cut of a spar does not lead to a catastrophic event.

In addition to the structural, architectural, safety and cost advantages, some potential aerodynamic advantages were identified in comparison to a mono-wing design. Due to the smaller chord and the staggered position of the wings with overlapping wings at their outermost region, the excited download of the downwash during hovering is considerably less as a result of a lesser total masking in areas of larger downwash velocity. Moreover, the large aspect ratio of both wings is considered to improve the lift-to-drag ratio and hence the aerodynamic efficiency of the wings. This, in combination to the lower interference drag within the transition to the fuselage, is expected to alleviate the aerodynamic disadvantages of a joined wing in terms of interference drag and the wings airflow interactions at the wing tip interconnection region between the intrados of the upper wing and the extrados of the lower. The increased wing distance and wing staggering towards the wing roots is considered favourable in terms of the aerodynamic interaction between the wings.

Preliminary FE- and CFD analyses, as well as statistical approaches were performed on a generic platform in order to quantify the potentials and possible drawbacks of the joined wing in comparison to a mono-wing configuration, including for both a pusher propeller configuration. The analysis confirmed a significantly increased static and dynamic stiffness, substantial weight saving potential on the wings, significant weight savings on landing gear and outstanding fail safe capabilities. In addition, the download was reduced and the drag turned out to be invariant for the same total lift.

As result of all these synergistic features the joined wing is deemed, in a global view of the aircraft, the most effective configuration for a high speed helicopter. A joined wing configuration comes up to be particularly suited for a high speed helicopter based on the compound formula with lateral propellers, rising from the combination of an essential upper wing with an advantageous lower wing.

In view of these potentials, Airbus Helicopters decided to adopt the joined wing concept for the Clean Sky 2 RACER project bearing the challenge of developing an entirely new wing configuration which offers clear advantages but involves a special degree of substantiation complexity, especially facing the wing`s static and dynamic behaviour and its interaction with the dynamic system and the airframe. The joined design is unique for rotorcraft applications and could represent the first commercially available joined wing aircraft in the history of flight as a logical step of all is benefits described above.

2.3 Historical Review on Joined Wings

The use of two interconnected non planar, self-supporting, closed wings has been often suggested and explored in the history of fixed wings. The origin is rather linked to the aerodynamic advantages in terms of the reduction of induced drag and the improvement of the span-efficiency factor for a bi-plane of closed wing configuration with rectangular arrangement and sufficient offset between the horizontal wings [4]. This arrangement is addressed as “boxed wing” and features an outstanding aerodynamic drag behaviour but a less efficient structure-mechanical (static and dynamic) behaviour due to the rectangular wing arrangement globally working as a beam framework rather than a truss construction. A modern example of such concept is the modernized An-2 demonstrator announced in 2015 by Sukhoi.

Other closed-wing arrangements entail a staggered diamond configuration with sharply interconnected and largely staggered wings. This configuration is typically characterized by the lower wing being connected to the lower front portion of the fuselage and the upper wings being sweeping backward and upward to connect the very aft upper portion of the fuselage or the tip of the vertical fin. These arrangements can rather be addressed as “joined wing” constructions. The principal advantages associated to these types of joined wing are the elimination of a down lifting horizontal tail, the mutually stiffening of the wings, the associated lower structural mass and the improved wing efficiency due to larger aspect ratios. The tip interference drag is considered marginal and minimized when no overlap is present in a plan view. The span efficiency is large with increasing the ratio of maximum wing vertical separation and the wing span [5]. Not only concepts with straight wing planforms but with variable contour have been as well suggested aiming an improvement of the loading and the structure-mechanical behaviour of the wing construction [9].

A further category of supported wings represents the “braced wing” concept, which rather represents a strut braced wing with one main wing, instead of two equivalent wings, being supported by a strut member. Larger structural efficiency and wing stiffness translate to increased wing efficiencies in terms of higher aspect ratios and lower wing mass [6]. Similar concept has been suggested by NASA and Boeing aiming a “Subsonic Ultra Green Aircraft”.

Most of the investigations on closed-wing, non-planar configurations are rather focused in aerodynamic aspects, but little emphasis is noticeable on a detailed multidisciplinary assessment of the aircraft as a whole aiming more than just generic evaluations of the potential improvements – or drawbacks – in terms of aerodynamics. Unconventional closed-wing designs are deemed promising rather facing their structural and architectonical characteristics than their aerodynamic features, being the structural efficiency its primary advantage [7]. It might turn advantageous in global terms even at the expense of some loss of aerodynamic efficiency in the local context of the wings.

The exploration of innovative closed-wing concepts with industrial relevance has been entirely devoted to fixed wing applications, such as for gliders, airliners, heavy transporters and even supersonic fighters. The fact that the joined-wing requires huge efforts in its prediction, evaluation and definition with a wide variety of interacting parameters is seen as one of the reasons why such concepts are only slowly progressing [9]. Its application of rotorcrafts appears to be something completely new, and, as is being demonstrated during the design process of the RACER, particularly well-suited for high speed rotorcraft configurations.

3. MECHANICAL WING PERFORMANCE

3.1 Interaction with drive shaft

As highlighted in the previous paragraph one design feature of the new wing configuration is the integration of the drive shaft as power train between main gear box and lateral propeller gear boxes. One parameter which influences the design and the stress analysis is the limit of the soft couplings in this power train: One soft coupling is intended to be installed at the junction of the drive shaft to the main gearbox, a second one is foreseen at the connection of the drive shaft to the lateral gearbox.

This state-of-the-art design of transferring torque moments between different gear boxes is now analysed within the structure-mechanic environment of a slender wing. On the one hand the low profile thickness limits the space for the movements of the drive shaft. On the other hand there needs to be adequate clearance between the rotating and the non-rotating parts for the elastic movements of the drive shaft relative to the wing.

Besides the deflections of the shaft several deflections are directly or indirectly applied to the structure-mechanic environment of the shaft and the wing respectively:

- In case of a classical support of the main gear box this type of support allows an elastic pendulum movement around the main rotor shaft's axis according to torque loads as well as secondary movements around the global x- and y-axis according to the applied mast moments.
- The lateral gear box also generates elastic movements around the propeller drive shaft according to the propeller thrust and in case of manoeuvers secondary movements around other axes.
- At the wing root the propeller thrust in combination with the lever arm of the wing span leads to a moment and in consequence to a rotation of the lateral gear box.
- The lift generated on the wings additionally bends the wing from a straight line to a bending curve. Then the shaft in the wing can be approximated by an almost straight line between the soft couplings and represents in this geometrical context a secant line within the bent upper wing. As the secant's length is smaller than the radian of the wing an axial movement of the shaft relative to the wing is generated.
- As the wings are attached to the upper deck and in addition to the subfloor group, they introduce the wing loads, the propeller thrust, and the inertial masses into the fuselage at different locations. This results in local and global deformations. These elastic movements lead to additional rotational and translational deflections.

All the rotational and translational movements of the wing, the drive shaft, the gear box, and the fuselage need to be considered and to be brought into a local context describing the relative movement between each other. The stiffness of the different components has an impact on the amount of angular and lateral movement of the drive shaft in the wing. These deflections finally need to be compensated by the soft couplings.

As the shaft rotations sum up to an extremely high number of revolutions the adjustment capabilities of the soft coupling are limited. These elastic capabilities normally are directly related to its size. However the space in the wings and the available design volume in the lateral gear box as well as in the main gear box area are limited. As a result, a compromise in soft coupling capability, aerodynamic efficiency, and stiffness requirement of all contributing components needs to be found. This was the scope of several studies at Airbus Helicopters which took place on global vehicle level.

In contrast to compression stresses the tensile stresses lead to fatigue limitation the soft coupling's characteristic. Thus the coupling's characteristic shows a higher durability in deflection cases tending to compression compared to tensile driven movements, see asymmetric normalized characteristic in Fig. 12.

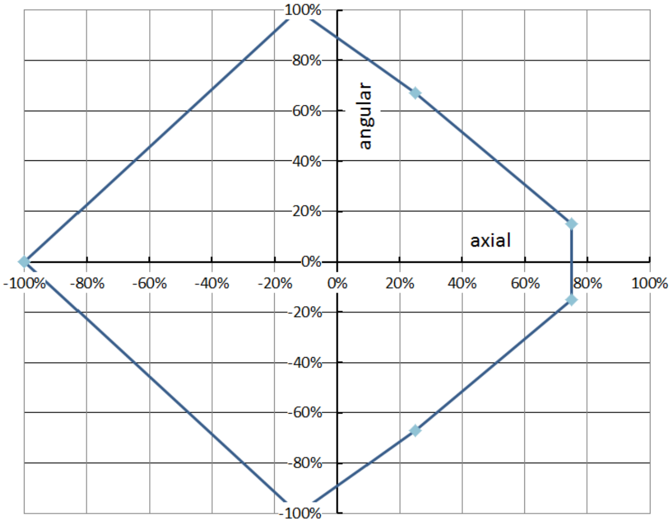


Fig. 12: Endurance limit characteristic of the soft couplings in normalized scale.

These limits of the soft couplings define the sum of acceptable movements of the whole structure mechanic system. The parameter studies with variation of the different amplifying and compensating effects (see above) showed a different behaviour of driving load cases at the inner coupling in comparison to the outer coupling, see Fig. 13 and Fig. 14.

The main cause for this behaviour is that the wing acts as cantilever arm for the rotor thrust: At the outer coupling the loads of the lateral rotor dominate the elastic movement. At the inner coupling the propeller thrust in combination with the cantilever arm of the wing span has a big influence. This is a main difference of the elastic system compared to the wing of the X³ demonstrator where flapping movements dominated.

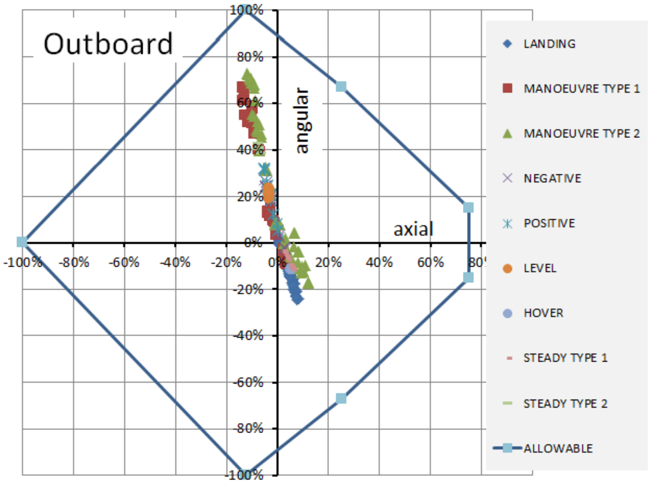


Fig. 13: Comparison of angular and axial movements (normalized) at outboard coupling for several flight load cases.

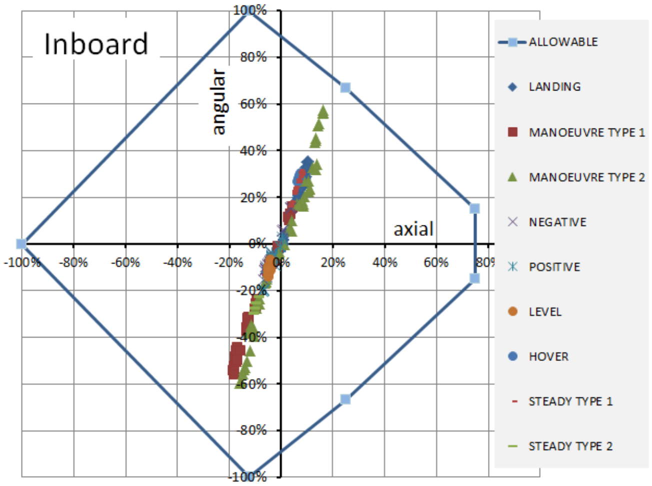


Fig. 14: Comparison of angular and axial movements (normalized) at inboard coupling for several flight load cases.

The loading condition of the left hand wings and right hand wings is different: On one wing side the lateral rotor is permanently in forward thrust mode, on the other wing side the propeller needs to supply forward or rearward thrust according to the flight condition. For example in hovering the full torque reaction is achieved by thrust of the lateral rotors in opposite direction of both lateral rotors whereas in with increasing forward flight speed the backward thrust decreases and even changes its sign. As shown in Fig. 15 and Fig. 16 left and right hand couplings have a different distribution.

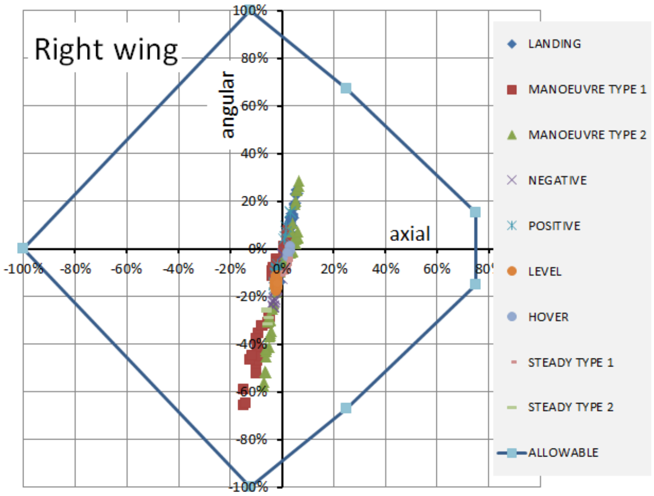


Fig. 15: Comparison of the angular and axial movements at the inboard coupling (normalized) on right wing side.

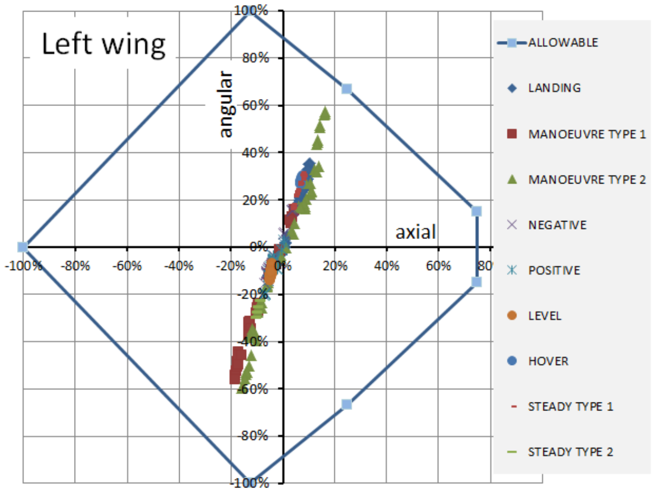


Fig. 16: Comparison of the angular and axial movements at the inboard coupling (normalized) on left wing side.

The performed studies showed that the deflections caused by the mechanical load cases do not violate the soft coupling’s elastic capabilities. Consequently the chosen wing configuration is stiff enough for this kind of application and provides a significant improvement of the formula of X³. This means that the requirements can be met without extensive stiffness improvements of the wing.

Nevertheless, a big number of coupling arrangements, wing designs, upper deck architectures and attachment strategies have been examined before an optimum of the different contributors of the coupling’s deflection was achieved. During those examinations an interesting behaviour of different wing-to-wing hinge positions has been detected. This will be detailed in the next chapter.

3.2 Wing-to-wing hinge position

During the pre-development phase a big variety of studies has been carried out to identify the influencing parameters and to compose the wing in a way which provides a good compromise between structural stiffness, weight and available space.

One of the examined parameters of the wing assembly is the position of the hinges as they influence the structure mechanic behaviour of the wing assembly. Without any hinge the wing would additionally act as framework being additionally loaded in bending. From a structural point of view load reaction in bending is inefficient in terms of weight due to its low utilization factor of the material. Fig. 17 shows for example two possible alternatives of the position of the wing interconnection hinge with respect to the upper and lower wing and the corresponding lines of action.

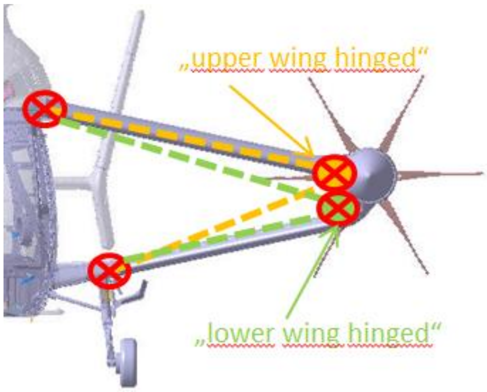


Fig. 17: Position of hinges or hinge lines respectively in the global wing architecture.

The positive effects of a hinged attachment of the wings to the fuselage were soon validated. The location of the hinge at the wing tips is one of the promising configurations. Scope of the studies was to minimize the axial and angular deflections in the soft couplings. In this context the different profile thicknesses and lengths of the upper and lower wing in combination with the stiffness of the interconnection area for the mounting of the gear boxes influenced the result:

- The upper wing has a bigger length than the lower wing. This leads to a lower stiffness of the upper wing compared to the lower wing.
- On the other hand the thickness of the profile in the upper wing is bigger compared to the lower wing which brings its bending stiffness up again.
- The wing interconnection area as load transferring part between upper and lower wing influences the stiffness at the wing tip.
- The interconnection area serves as load introducing part for the reaction forces of the lateral gear boxes or lateral rotors respectively.

In superposition to these geometric conditions the different load cases resulted in a high number of loading conditions at the different areas of the wing assembly. Thus one of the steps was to identify which loading condition drives the angular and axial deflections for different hinge positions. Due to the big amount of loading conditions and in order to reach several optimisation goals at the same time, a computer aided optimization (CAO) has been performed for the two conditions described above: lower wing is “hinged” or the upper wing is “hinged”.

The optimization results for both options differ significantly, especially when looking at single effects of the objective function. In case the lower wing is hinged and the deflections are to be minimized, the reinforcements are located in wide areas of the upper wing, see Fig. 18.

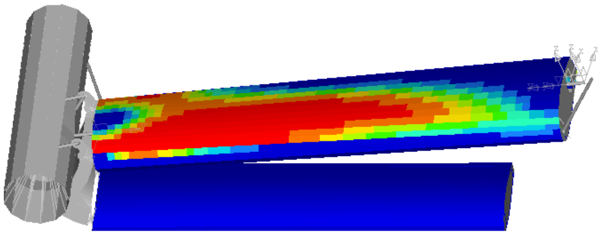


Fig. 18: Thickness distribution on the wings in case of minimum angular deflections for a “lower wing hinged” configuration (view from top front).

When considering a configuration with a hinge at the upper wing, reinforcements are located in the lower wing in case of minimizing the deflections at the couplings, see Fig. 19. Finally this is according to the expectations because due to the additional bending moment in the lower wing reinforcements are needed.

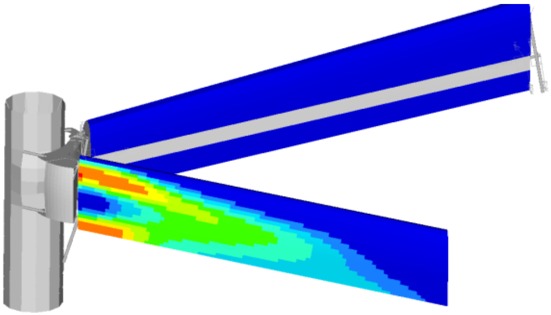


Fig. 19: Thickness distribution on the wings in case of minimum angular deflections for an “upper wing hinged” configuration (view from below).

Even more complex is the optimization of the overall stiffness say minimizing the angular and axial displacements for both soft couplings as a whole. This is subject of the current investigations which are almost ended. After their final interpretation and incorporation this will be discussed in more detail in a future paper.

For the time being, an adequate compromise between required wing stiffness, weight, coupling design, and allocated space has been defined for the current wing design status and is basis for the next steps in the development work.

4. AERODYNAMIC WING PERFORMANCE AND STABILITY

4.1 Stability and architecture

A drawback of the X^3 mono-wing configuration was its influence on the longitudinal stability. The presence of a wing degrades the horizontal stabilizer efficiency by a deflection effect. Moreover it was not possible to move the wing backward to make it contribute to stability as its longitudinal position was imposed by the transmission shaft linking the lateral gearbox to the main gearbox. In order to compensate these two effects, the horizontal stabilizer had to be oversized.

With the joined wing configuration, the upper wing only has to contain the transmission shaft. The integration of the landing gear inside the lower wing makes it compatible with an aft position thus contributing to the longitudinal stability. It is now possible to significantly reduce the size of the horizontal stabilizer and minimize the associated problems at low speed (download and pitch-up).

4.2 Performance

The choice of the joined wing was made after a wind tunnel test during the preliminary design phase. A standard mono wing similar to X^3 was compared to a first version of the joined wing. In terms of maximum lift and angle of stall, both configurations were equivalent. The drag of the isolated joined wing was slightly higher but after integration on the airframe, thanks to a better wing / fuselage interference, the drag was found also equivalent. The performance of a lifting surface cannot be assessed only as an isolated element, the question of the integration to the complete airframe is also a determining factor.

An additional reason for the choice of the joined wing was its reduction of download in hover induced by the main rotor downwash. CFD computations in hover showed a reduction by 50% of the lower wing contribution (Fig. 20).

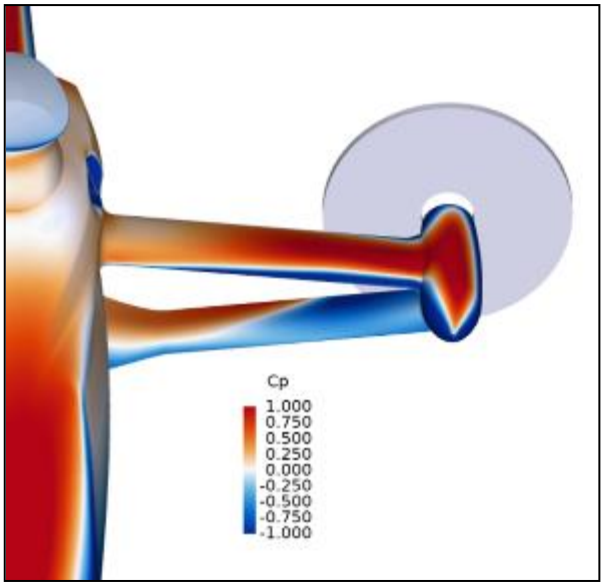


Fig. 20: Pressure coefficients in hover obtained by CFD in hover.

A complete optimization loop was launched by the aerodynamic team – soon supported by the aero-acoustic core partner and the structures team – to define the most effective wing arrangement in terms of the wing tip gap and the associated dihedral angle of the lower wing. Different settings were explored as depicted in Fig. 21, varying from a pure truss (joined wing) arrangement with minimum gap (grey) to a boxed-wing with a 0°-dihedral lower wing (pink). The main subjects were:

- Airfoil, twist, taper: these are general parameters defining a wing. They were adapted ensuring the compatibility with mechanical, structural and operational constraints and led to constant chord, untwisted wings.
- Wing-to-wing gap distance: a long gap reduces the interference between the lower and upper wings but requires larger non-lifting surfaces for wings / nacelle junctions with their associated profile drag. In addition, the stiffness and structural efficiency of the wing arrangement is considerably reduced with increasing gap due to increased wing bending. Different configurations were computed by CFD (Fig. 21) and an optimum angle of 12° was found regarding aerodynamic and structural requirements.
- Maximum lift and stall: helicopters are appreciated for their manoeuvring capabilities. They are designed to sustain high load factors up to 3.5 G (CS29.337) and a wing significantly increases the achievable load factor at high speed. In the interest of safety, the wing is designed not only to improve the performance and manoeuvrability but also to offer a safe behaviour at and beyond stall. The stall is reached beyond the design load factor in all cruise phase. In addition, the stall is smooth and sequenced on lower and upper wing to avoid a sharp loss of lift and sudden pitching moment (Fig. 22). A very linear behaviour about the pitch is finally obtained, including around the stall angle (Fig. 23).

Fig. 21: Explored settings of tip wing gap and lower wing dihedral.

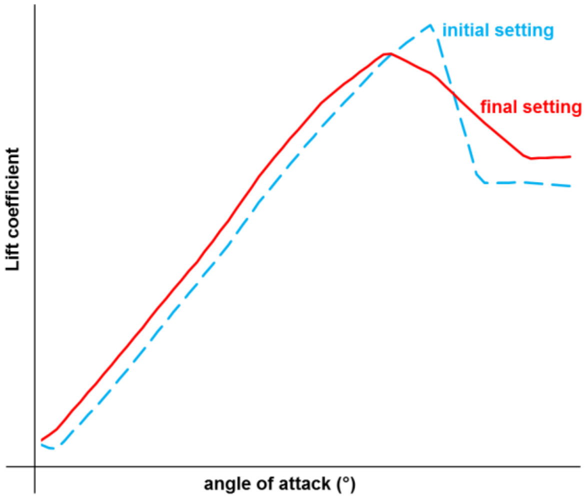


Fig. 22: Isolated wing lift coefficient as function of the angle of attack (wind tunnel results).

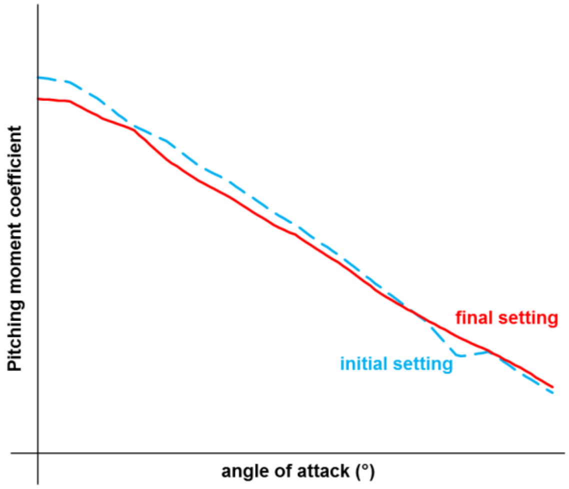


Fig. 23: Complete HC pitching moment as function of the angle of attack (wind tunnel results)

Each of the four surfaces of the box wing is fitted with a plain flap (Fig. 24). The flaps are automatically adjusted to allow the main rotor working with its optimum lift whatever the weight and speed of the rotorcraft and the air density.

The flaps are not used as primary controls. The control of lift and roll axis is always ensured via the main rotor commands (collective and cyclic sticks). The wing flaps are just used to optimize the trim with slow control laws.

Fig. 24: Wing flaps.

4.3 Wind tunnel tests

CFD was intensively used by Airbus Helicopters for the pre-design and design phases. This is a precious tool to explore a lot of configurations at reasonable cost, but a final validation in Wind Tunnel was necessary. Stability and performance were successively assessed at Airbus Marignane (FR) (7.1 m^2 section, 40 m/s) and Airbus Filton (UK) (11.2 m^2 section, 100 m/s) facilities. The mock-up was modular to allow comparing different configurations or components such as engine cowlings, tail parts, rotor head and of course wings. Rotating parts were also available.

Aerodynamic interactions are a frequently encountered subject in helicopters domain and they can have different consequences such as instability, vibrations (tail shake), loads and noise. For example, the influence of the combined wake of a wing and propellers located at trailing edge on the tail parts was observed at Filton WT with an active set of propellers (Fig. 25).

The conclusion was that the "H tilted" shape of empennage was the most robust configuration to this wake effect. The X^3 demonstrator had obtained excellent results with its quite similar H tail but the change of propeller position associated to a new fuselage shape needed a complete assessment of the interaction.

Fig. 25: Performance and Handling Qualities mock-up at Airbus Filton Wind Tunnel – configuration with active propellers

To go in more detail, a scale 1:1 mock-up of the wing and propeller was tested at the RUAG Aviation Emmen (CH) Wind Tunnel (35 m^2 section, 68 m/s) (Fig. 26).

Fig. 26: Scale 1:1 wing and propeller at RUAG Aviation Emmen Wind Tunnel

These scale 1:1 tests were dedicated to:

- Performance: check the power and thrust prediction of the propeller located at the wing trailing edge.
- Loads: check the propeller blades dynamic loads that may result from the wing wake.
- Noise: propellers in pusher position may be considered as noisier on turboprops applications. The engines exhausts blowing in front of the blades are mainly responsible for this drawback. As the RACER nacelles only contain a gearbox, this effect is not feared, the tests were focused on the wing wake. Different configurations of trailing edge were tested to validate the wing/propeller interference level. Although the Emmen facility is not an anechoic wind tunnel, it was possible to calibrate the test installation and compare the different configurations. An excellent

comparison with the acoustic results of our core partner was found.

5. CONCLUSIONS

- The arrangement of joined wings with positive stagger at the fuselage transition and with overlapping wings at their interconnection region leads – in combination with pusher propellers allocated at the interconnection region – to a multidisciplinary synergetic solution especially suited for high speed rotorcrafts.
- The developed joined wing configuration represents an overall optimum solution with regard to structure-mechanical (weight, robustness and simplicity), architectural (integration and simplicity of main landing gear, compatibility and accessibility to mechanical deck, compatibility to dynamic system), service (safety, fail safe, low noise) and aerodynamic aspects.
- The joined wing provides for a large stiffness in the most demanded working plane of the wing and hence outstands by an improved compatibility to the requirements of the transmission to the lateral propellers, especially facing the increased wings span.
- During the pre-design phase, the mono wing and the joined wing were compared by CFD and wind tunnel. The joined wing was found equivalent in terms of performance (lift-to-drag ratio, maximum lift).
- Thanks to the aft position of the lower wing, the joined wing significantly contributes to the pitch axis stability which allows reducing the size of the horizontal stabilizer.
- The noise penalty of pusher propeller configuration generally observed for airplanes is not applicable to this configuration. This penalty comes from the engine exhaust interaction whereas the RACER nacelle only contains a transmission gearbox. Moreover a special attention was devoted to the wing / propeller interference noise.
- The joined wing includes four flaps to optimize the main rotor lift and reach its best Lift-to-Drag ratio whatever the rotorcraft weight and altitude in trimmed condition.
- The intensive usage of CFD allowed reducing the amount and cost of wind tunnel tests. A final validation in Wind Tunnel with good comparison with CFD was performed. A scale 1:1 test of wing and propeller was run to observe and validate complex interactional aero-acoustic phenomena.

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