AERODYNAMIC DESIGN OF THE A400M HIGH-LIFT SYSTEM

DANIEL RECKZEH
Airbus, Aerodynamics Domain
Bremen, Germany
Daniel.Reckzeh@airbus.com

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Abstract

The aerodynamic design of the A400M high-lift system is characterized by requirements very dissimilar to the design of "classical" Airbus high-lift wings. The requirements for the "Airdrop-mission" (parachutist & load dropping) provide additional design constraints for the layout of the high-lift system.

Leading edge devices were avoided to keep system complexity low. This required a carefully integrated design of the wing leading edge profile & the nacelle shapes.

The interaction of the propeller wakes with the wing appeared to be a major effect on the high-lift wing flow topology with significant impact on its maximum lift performance.

Fixed-Vane-Flaps on simple Dropped-Hinge Kinematics were selected as trailing edge system solution. While being beneficial for lower system complexity and weight the layout represented a significant challenge for an optimised aerodynamic design. The solution therefore had to be carefully optimised in several loops with the use of intensive high-Reynolds number windtunnel testing in direct coupling with the CFD-based design work.

2D & 3D RANS CFD methods were used the first time as key tools in the high-lift design process to deeply optimise the layout already on a fully theoretical basis.

1 Challenges of the A400M configuration for aerodynamic design

The variety of missions and range of operational requirements (high and low altitudes, logistic and tactical missions, unpaved runway operations) dictate a much different configuration than for a civil transport aircraft. The configuration optimisation must consider all aspects of the design, and achieve a proper balance between aerodynamic performance, weight, handling characteristics, integrated logistic support, cost, amongst many other aspects.

Fig. 1: Airbus A400M

As a result of all of these considerations, several features of the wing configuration are significantly different from normal Airbus aircraft:

- The wing configuration has some clearly different characteristics, such as the low sweep, and the straight tapered planform, and some less obvious ones such as the omission of moveable leading edge devices, a relatively high-performance flap system and the relatively large spoiler area;
- The turboprop powerplant installation mounted directly onto the wing and the propeller slipstream interference effects

require much different considerations than a conventional pod/pylon mounted turbofan engine;

- Many other differences must also be considered in the aerodynamic design philosophy of the wing, including, for example, the high mounting position of the wing on the fuselage, integration of the flap mechanism fairing design, possible adverse interference between the wing and the undercarriage sponsons, as well as many other issues.

As well as integrating all of the unique configurational aspects outlined above, the range of mission guarantees requires a particularly fine balance to be struck between the high-speed and low-speed / high-lift performance capabilities, which in itself, has proved a particularly challenging aspect of the design of this wing.

2 Design drivers for the high-lift wing

The aerodynamic design of the A400M high-lift system is characterized by requirements very dissimilar to the design of "classical" Airbus high-lift wings. Usually both the climb-performance (i.e. the lift-to drag-ratio) of the take-off-configuration and the approach speed (i.e. the maximum lift) of the landing configuration are driving parameters for the field performance. However on A400M the requirement for the "Airdrop-mission", i.e. the in-flight dropping of parachutists or loads on parachutes represents a further critical design point. This mission drives the requirement for a high lift at a certain aircraft weight and speed in combination with different pitch attitudes for gravity airdrop and parachute extraction. During the design process it was found that these requirements became very important for the layout of the high-lift configuration.

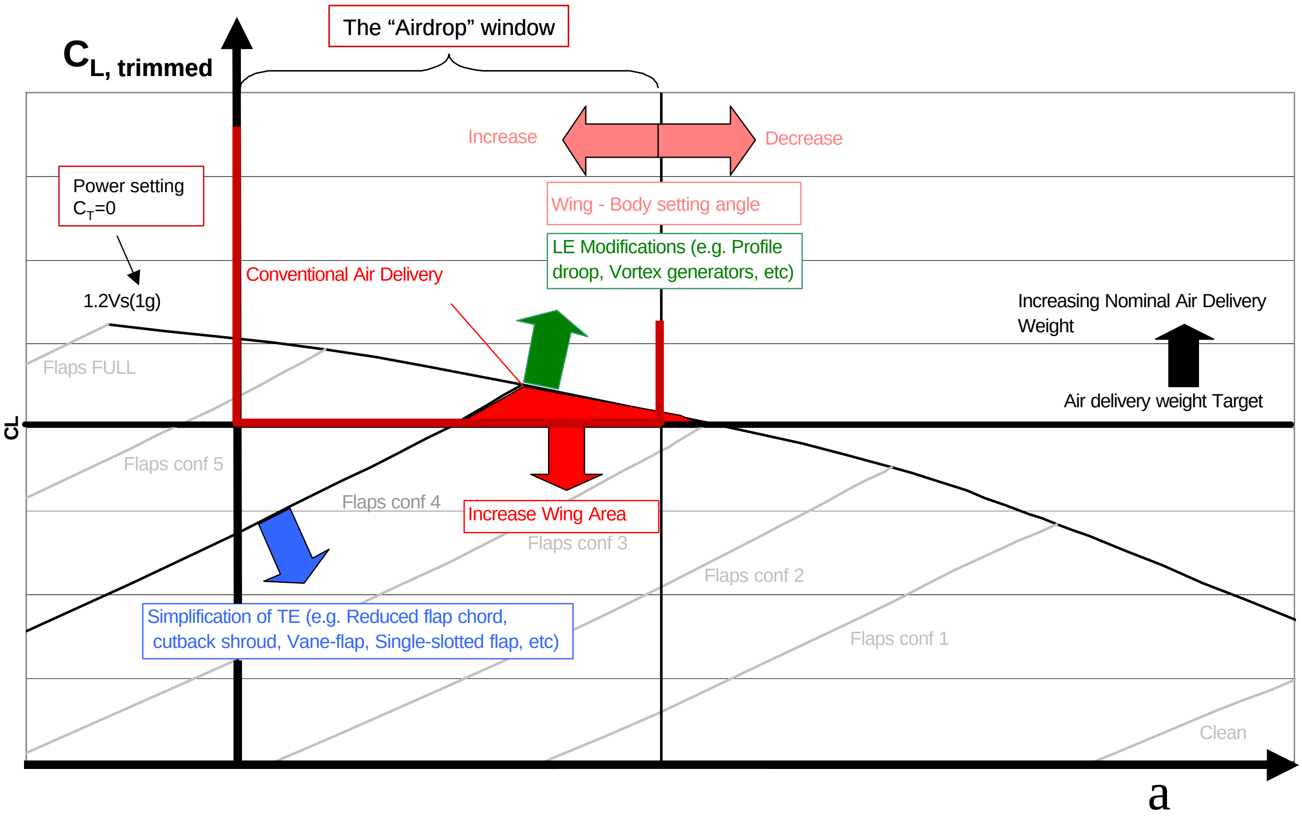

Fig.2: "The Airdrop Diagram" – Design target for the high-lift performance

Far more than for the cruise wing the aerodynamic design of the high-lift wing is significantly driven by multidisciplinary constraints. Besides the requirement for a proper integration of the high-lift shapes into the cruise wing design and the need for a kinematics system able to deploy the flap according to aerodynamic requirements it is essential to design a solution which is simple and light as well as easy to manufacture.

Finally, the high-lift wing has to represent a best compromise between the involved disciplines. For an optimised solution a highly integrated process chain is mandatory. For the aerodynamic design of the A400M high-lift system the aerodynamic design team had to iterate its design work closely-coupled as well with the aerodynamic design & integration of the cruise wing and powerplant as with the high-lift- and wing engineering, specific design & build teams (i.e. systems, structures, manufacturing, costing, etc).

3 Development of the high-lift concept

A variety of possible solutions for the layout of a high-lift wing exists. A combination of a Slat as leading edge device and a Single-Slotted Flap driven on Track-kinematics as trailing edge solution became the Airbus standard solution from A320 up to A380. Due to the lower cruise Mach-number of the A400M the sweep of the wing is lower than on other Airbus aircraft, which benefits the high-lift performance of the “basic” wing, as well as the significant propeller wake effect on the wing lift performance. Facing the customer requirement to keep system complexity low (“a simple and rugged design”), it was decided to avoid leading edge devices and limit the moveable devices to a flap system at the trailing edge.

3.1 Integration of the slat-less leading edge & engine nacelles

The decision to avoid leading edge moveables however required an even more carefully integrated design of the leading edge profile in order to best benefit the high-lift performance while not compromising the cruise performance. The final shapes show a visible amount of “droop” (i.e. a thicker profile shape with lowered nose-line) at the leading edge relative to “classical” profiles only optimised for cruise flight. This helped to contribute via an improved high-lift performance already of the basic cruise wing profiles themselves.

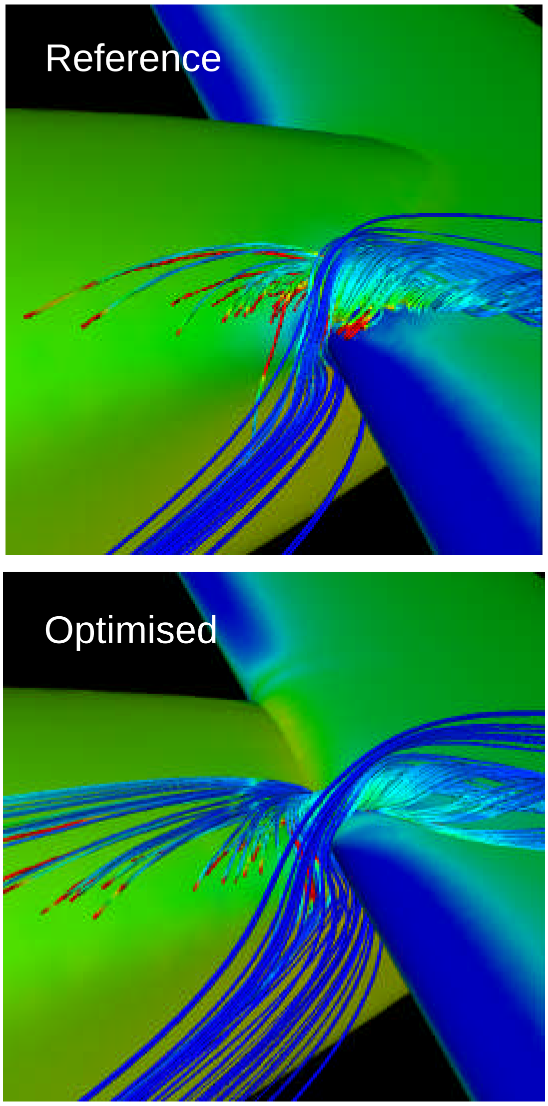

Fig 3: 3D-Flow topology at the leading-edge/nacelle intersection (3D RANS CFD at high A/C incidence)

This approach was taken especially in the regions of the leading edge where the flow is prone to separate earlier due to local disturbances of the engine nacelle integration. Also the nacelle shape was optimised to limit the adverse implications on the flow quality in this junction. However, hard constraints related to the structural solution for engine mounting and systems integration limited the aerodynamic design freedom in this area. Fig. 3 shows the beneficial impact of the reduction of the upper surface "footprint" on the strength of the vortex emanating from the nacelle/wing leading edge junction.

3.2 Power effect on high-lift performance

With the propeller working in high-thrust conditions the propeller effect on wing lift is significant, i.e. the additional lift increment can reach the order of magnitude of the lift increment of the complete flap system. Also the drawback on the separation behaviour of the wing is large, as the upwash/downwash in the propeller wake overlays the free onset flow. In Fig.4 the effect of a medium power setting on the wing pressure distribution and streamlines is visible. The suction peaks are increased in the wake of the up-beating blades inboard of the inner nacelle and outside of the outer nacelle.

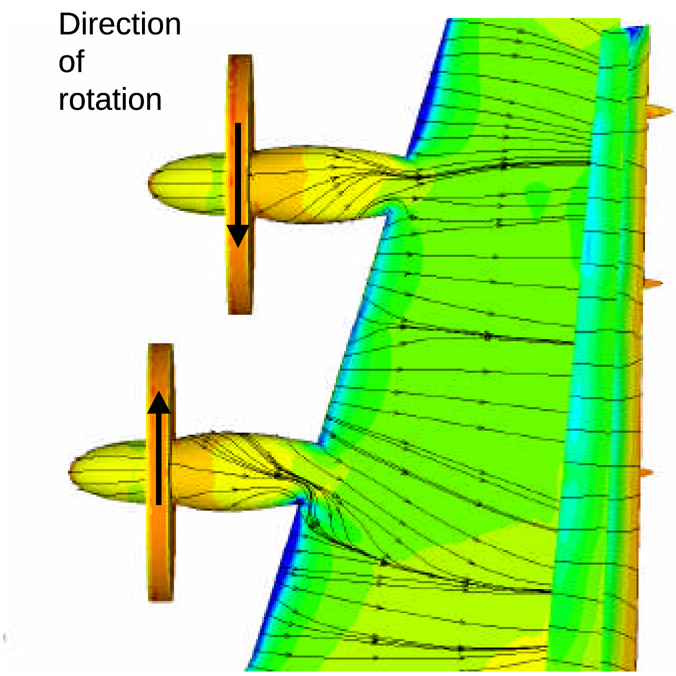

Fig. 4: Effect of propeller wake on wing pressure distribution and streamlines (3D RANS CFD)

The initial aircraft configuration was intended to have, as usual for common propeller aircraft, an arrangement with all propellers rotating in the same direction (e.g. as on the C130). Subsequent benefits in part-count, cost and logistics are evident for such a solution, however at the price of a fully asymmetric aircraft configuration.

The design verification and data generation work indicated that with the very high installed engine power the repercussions of an asymmetric configuration on flight ranges at the border of the envelope are significant. This would result in the need to cut off these ranges via severe flight range limitations by the flight controls and therefore also visibly impacting the potentially achievable performance. It subsequently was finally decided to select a symmetrical configuration with all propellers rotating "down between engines". This arrangement has shown to be the optimum solution of propeller rotation for a symmetrical A400M configuration with regard to a best balance between cruise and high-lift performance implications as well as cabin noise considerations.

3.3 Definition and optimization of the trailing edge system

Without a leading edge device applied, the demand for delivering the necessary high-lift performance relies fully on the trailing edge system. In the initial trades, it became clear that the required contribution of the flap system to the maximum lift performance is too demanding for the "Airbus standard" solution with a simple Single-Slotted Flap. Therefore a Double-Slotted Flap (DSF) system, comparable to the Airbus A321, was selected as the first baseline solution. With its selected large 30% chord layout it provided the required high-lift performance, however with significant disadvantages for the overall aircraft design. Airdrop performance is not necessarily enhanced by a more powerful high lift system as it may lead to a violation of the airdrop window in terms of the required aircraft incidence range as indicated in Fig.2.

Also, for the baseline DSF solution the subsequent impact on system complexity, tail size and resulting weight appeared to be more and more conflicting with the aircraft weight situation. Therefore the approach was taken to find a well-balanced solution, fulfilling all design requirements, a minimum weight. A range of downsized double slotted flaps was considered, however the stringent weight requirements finally pushed towards a step change in the design.

This was the starting point of the design solution of a so-called Fixed-Vane Flap on Dropped-Hinge Kinematics. While providing striking low complexity, a pivoted kinematics usually allows only the optimisation of only one flap deployed configuration, while all other settings are simply resulting from the subsequent hingeline. This solution was therefore not yet realized on Airbus wings, as the concept never provided sufficient flexibility to optimise performance for various mission requirements, i.e. a range of take-off and landing configurations. However due to the different requirements for the A400M high-lift wing, it now could be considered as a suitable solution.

The Fixed-Vane Flap is in principle also a Double-Slotted Flap, however with a fixed assembly of the smaller first flap (the “vane”) to the second (“main flap”) and commonly used on various aircraft (e.g. BAC 1-11, DC9, DC10). A kinematics system between the flap components is avoided, however the vane has to be fully retractable inside the cruise wing in order to cover the fixed slot. The Dropped-Hinge Kinematics causes the biggest gain in complexity and weight. Instead of the complex track & carriage mechanism, the deployment on a circular path enables a support structure with a simple single hinge.

While being beneficial for complexity and weight the solution is far from being optimum for the aerodynamics design freedom and therefore detrimental to an unconstrained optimised performance. As mentioned above, instead of a deployment path optimised for all settings the circular path allows only to optimise the slot (gap and overlap) for one setting (e.g. full flaps for landing or the Airdrop setting). This setting defines the hingeline location and

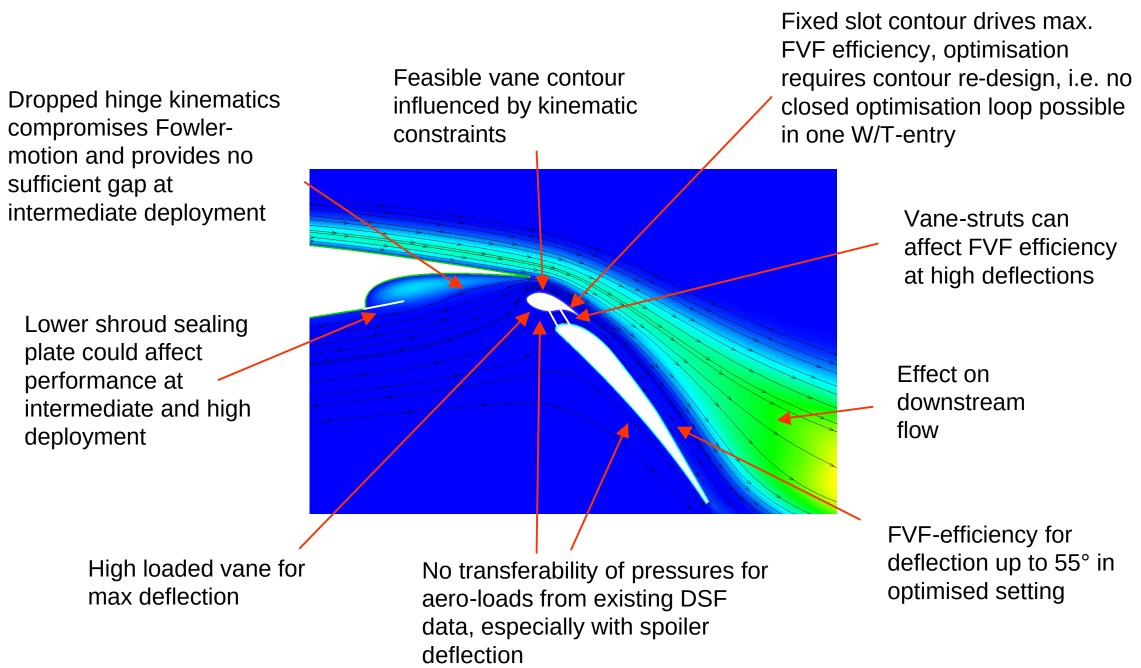

Fig. 5: Aerodynamic Design challenges

all other intermediate settings resulting. Especially the intermediate positions can be compromised by a slot, which results to be apart from the aerodynamic optimum and partially even divergent slot shapes can result which can cause separating flow on the vane with reduced lift performance and vibration. Therefore the design point for the circular motion had to be carefully selected in order to enable an efficient flap flow up to the highest deflection while maintaining acceptable flow quality at intermediate deflections.

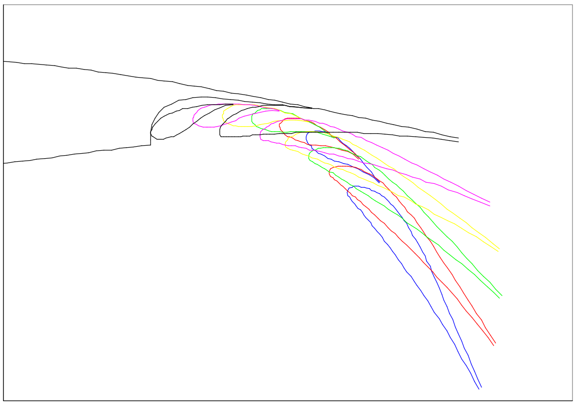

Fig.6: Fixed Vane Flap on Dropped Hinge Kinematics deployment path principle

The shape design especially of the vane is closely coupled to the constraints from the dropped hinge kinematics. As the slot between the vane and the main flap is fixed the vane has to be fully retractable inside the main profile. This requires a (usually moveable) sealing plate at the lower surface, which covers the vane and constrains the available space for its leading edge shape. In addition, the vane upper surface shape is constrained by the deployment path and the spoiler lower surface. A droop functionality of the spoiler to control the gap can help to ease this situation (as on C17).

On A400M the need for this spoiler droop functionality as well as for a moveable lower surface sealing plate could be discarded by carefully adapted aerodynamic design. This further minimized the complexity of the trailing edge system.

The vane and flap shapes were optimised in several steps leading to a careful choice in the ratio between flap chord, shroudline and split between vane and main flap elements.

4 CFD & Windtunnel testing approach for design verification

For a classical jet-powered transport aircraft configuration the majority of windtunnel testing can be conducted without engine exhaust simulation, but with a through-flow nacelle simulation the relevant flight-idle setting of the jet engine.

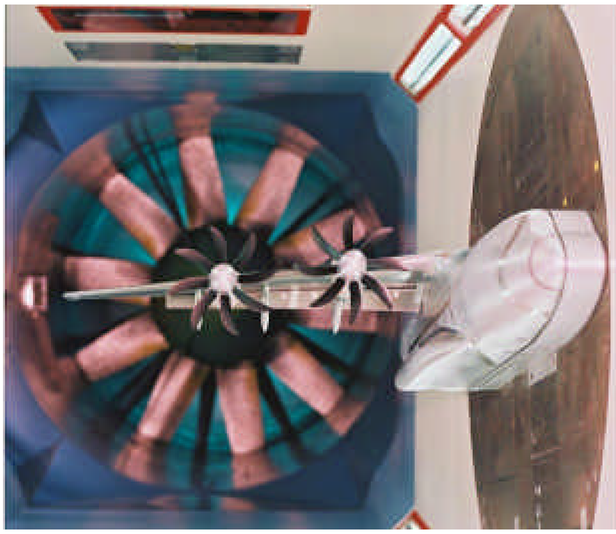

Fig.7: Powered A400M High-Lift halfmodel in the Airbus Low-Speed Windtunnel Bremen

On A400M however, the strong impact of the propeller wake on the wing flow topology led to the necessity to conduct windtunnel testing for the majority of tasks with engine simulation. Furthermore, the power setting of the engines provide an additional degree of freedom, which has to be verified on top of the usual parameters.

Simulation concepts with air and hydraulic driven engine simulators was developed and applied to the relevant high-lift models. Fig.7 shows a halfmodel configuration with air-driven TPS, which was the key workhorse for the development & optimisation of the high-lift concept. It was continuously updated to selected design states tested in the Airbus Low Speed Windtunnel Bremen at low Reynolds number and in the Onera F1 windtunnel at high Reynolds-number conditions.

For complete aircraft design verification & data generation further model chains were established. Fig. 8 shows the most complex complete model concept used. It was tested in the DNW-LLF ('Large low speed facility') and included four driven engine simulators capable to simulate very high power settings.

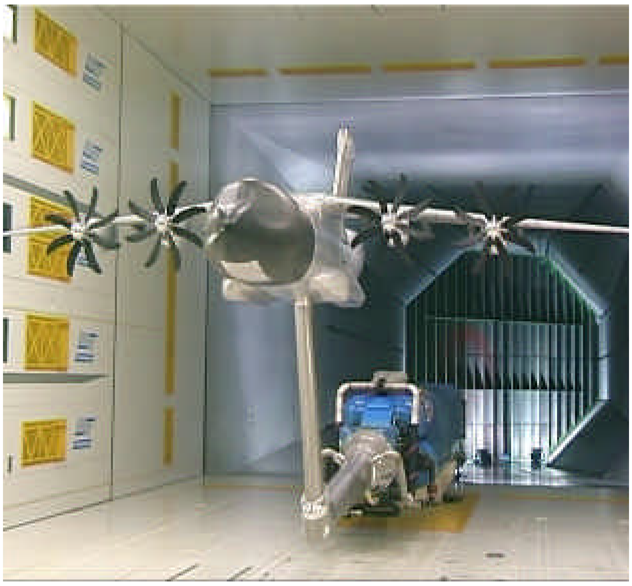

Fig.8: Powered A400M High-Lift complete model in the DNW-LLF windtunnel

On A400M high-lift aerodynamic design advanced CFD-methods (2D and 3D RANS; here: the DLR-TAU code on hybrid meshes) could be used for the first time fully embedded in the design-process with its quick turn-around cycles. This allowed already a deep optimisation of the aerodynamic design solution before conducting final 3D refinement in windtunnel testing. The shape design solutions were selected fully based on 2D / quasi-3D CFD sectional optimisation with full 3D CFD benchmark calculations (Fig.9).

Further high-lift design tasks were solved directly with 3D CFD, e.g. the integration of the nacelle / wing leading edge (Fig.3 & 4).

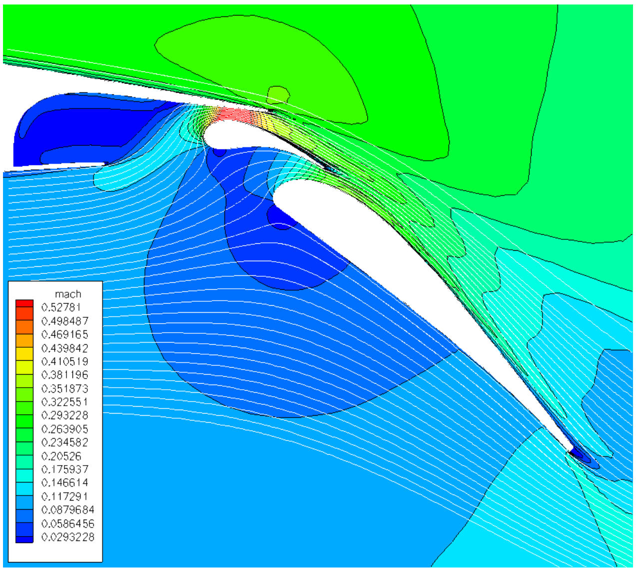

Fig.9: CFD (2D RANS) simulation of flow around a fixed vane flap section

As "high-end" 3D CFD applications also special tasks beyond the capability of classical industrial windtunnel testing were addressed, e.g. the prediction of the propeller flow features on the complete configuration or the prediction of the downstream flow field behind the deployed high-lift system, in proximity to the fuselage with doors & ramp opened (Fig.10).

5 Conclusions

The high-lift requirements and the developed solution for A400M are considerably different to the usual Airbus high-lift systems, i.e. a complete different design approach had to be taken.

The challenges of the integration of the high-powered propeller engines was managed by the intensive use of powered windtunnel testing which in itself was a challenge to be developed and qualified.

The design work for the Fixed-Vane Flap on Dropped-Hinge Kinematics had to be conducted in very short time after the change from the initial Double-Slotted Flap system. From scratch to delivery of the final master-geometry shapes, only about 2 years were given. This demanding task was possible only thanks to the availability and the intensive use of advanced CFD methods for direct design verification and subsequent windtunnel testing conducted in close coupling to the CFD-based design work.

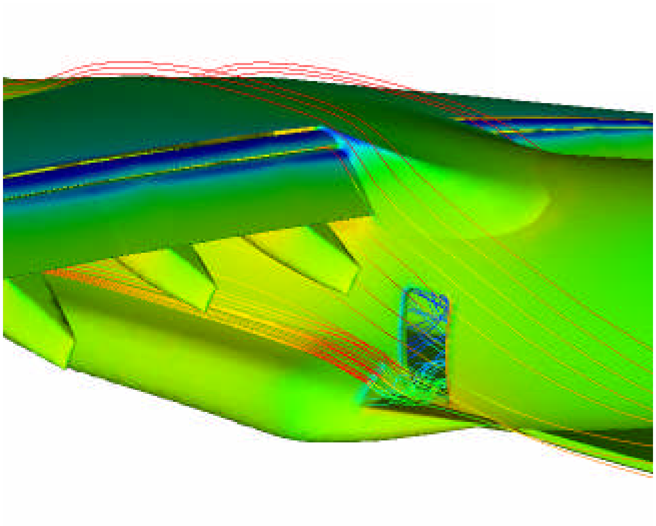

Fig. 10: CFD (3D RANS) assessment of the downstream flow quality behind the complete aircraft in high-lift configuration [1]

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