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Unsteady Flow Simulations of an Over-the-wing Propeller Configuration

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The aerodynamic integration effects of an embedded over-the-wing propeller at take-off conditions are discussed based on steady and unsteady Reynolds-averaged Navier-Stokes flow simulations. In contrast to the rotating blade and hub geometry, the steady computations utilized an actuator disk model with blade element theory enhancement to investigate the mutual influence between installed propeller and wing with sufficient accuracy. A simplified high-lift geometry of this channel wing concept is compared to a conventional tractor configuration. While the general over-the-wing integration effects, such as lift-to-drag ratio improvement and deteriorated propeller efficiency, are already captured by inexpensive steady simulations, only unsteady computations with full propeller geometry reveal some important flow details. The most striking unsteady effect is the interaction of the blade tip vortex with the boundary layer of the wing which only occurs at the channel wing due to the close coupling. As a consequence the low momentum fluid detaches above the flap leading to a comparatively low lift coefficient.

Nomenclature

c	=	chord length of CFD geometry
c_d	=	section drag coefficient
c_l	=	section lift coefficient
c_p	=	pressure coefficient $= \frac{p-p_\infty}{q_\infty}$
C_D	=	drag coefficient of aircraft $= \frac{D}{q_\infty S}$
C_L	=	lift coefficient $= \frac{L}{q_\infty S}$
C_P	=	shaft power coefficient $= \frac{P}{\rho_\infty n^3 D_p^5}$
C_T	=	thrust coefficient $= \frac{T}{\rho_\infty n^2 D_p^4}$
D_p	=	propeller diameter
J	=	advance ratio of the propeller $= \frac{V_\infty}{n D_p}$
n	=	rotation frequency of the propeller
p	=	static pressure
q_∞	=	dynamic pressure of freestream
S	=	wing area of CFD geometry
s	=	semispan of CFD geometry
S_{ref}	=	wing area of reference aircraft
t_{loc}	=	section thrust of propeller blade
T	=	thrust of one engine
V_∞	=	flight velocity, freestream velocity
x, y, z	=	cartesian coordinates, as subscript for direction

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α	=	angle of attack (AoA)
β_{75}	=	propeller blade pitch angle (at 75 % radius)
ϕ	=	propeller rotation angle
η_P	=	propeller efficiency
μ_t/μ	=	eddy viscosity ratio
ρ_∞	=	density of freestream

I. Introduction

FORECASTS project a capacity shortage of the major hub airports in the near future, especially in Europe and the USA¹. The collaborate research centre SFB 880 (funded by Deutsche Forschungsgemeinschaft DFG) investigates the technologies for a commercial Cruise-Efficient Short Take-Off and Landing (CESTOL) aircraft which can operate from existing small airports in an air traffic network with more point-to-point connections. A reference configuration with turboprop engines in tractor configuration as well as internally blown flaps has been developed in an early stage of the research centre by using the Preliminary Aircraft Design and Optimization tool PrADO² (see Fig. 1 for aircraft systems layout). At similar cruise performance and direct operating costs (DOC) as a state-of-the-art transport aircraft with passive high-lift devices, it can operate from 800 metre-long runways³.

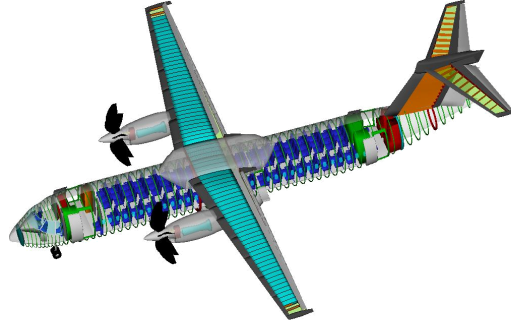


Figure 1. Preliminary design of reference aircraft with CESTOL capabilities.

The presented work is based on the results of a sub-project in the SFB 880 framework that focuses on over-the-wing propeller integration at the CESTOL aircraft. This kind of engine location was published and later patented by Johnson^{4,5} in the 1980s. A major advantage of such an arrangement is considered to be its noise shielding capability which was confirmed by aeroacoustic simulations. At takeoff, the sound pressure level at the ground could be reduced by 6 dB compared to a conventional tractor configuration⁶ which is of particular importance considering the open rotor noise issue. Furthermore, embedding the propeller into a channel wing is beneficial to minimize the nose-down pitching moment due to thrust⁷ in comparison to a plain over-wing design. A similar configuration was experimentally investigated by Englar⁸ to reach extreme lift coefficients. Steady Reynolds-averaged Navier-Stokes (RANS) simulations of the SFB 880 configuration with actuator disk predict that, at least for takeoff conditions, the close over-wing integration leads to a trade-off between propeller and wing performance. While the propeller loses 20% of its efficiency due to a considerably higher inflow velocity above the suction side, the wing achieves twice the lift-to-drag ratio. Taking into account both above-mentioned effects, such integration still reaches a 2-3% higher climb angle than a conventional tractor design⁹.

This paper shall validate these findings through comparison with high-fidelity unsteady RANS simulations. In addition, new flow details and integration effects are expected by computing the full propeller with

its blade geometry. For example, the blade tip vortices could not be simulated by the actuator disk model of the steady computations but may interact with the wing flow. The farfield geometry with its symmetry boundaries at both ends of the simplified rectangular wing was not changed to focus on the propeller installation effects. As in previous work^{7,9}, the channel wing performance in terms of lift-to-drag ratio and propeller efficiency is compared to the reference tractor configuration.

II. Test Case and numerical setup

A. Configurations and boundary conditions

A total of four CFD computations will be evaluated in this study. More precisely, a conventional tractor configuration is compared to an embedded over-the-wing propeller configuration, referred to as “channel wing”, see Fig. 2.

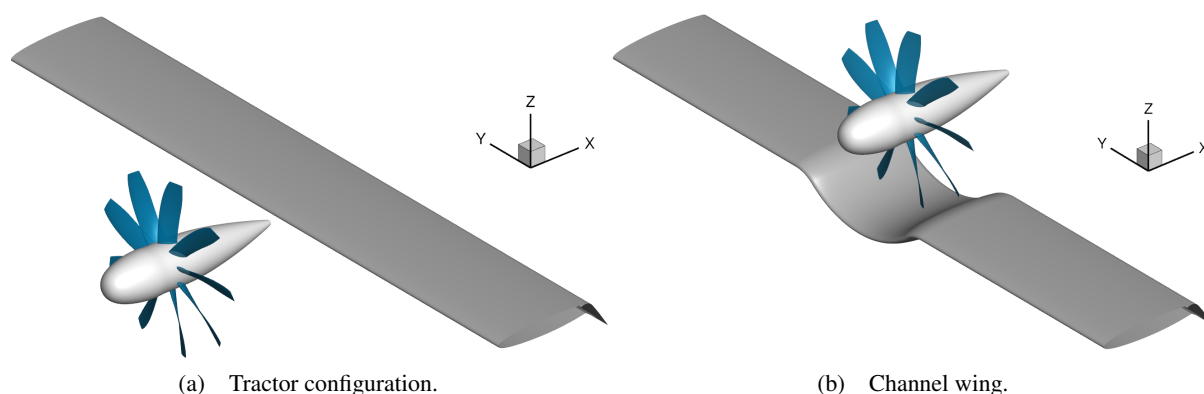


Figure 2. Investigated propeller-wing configurations.

Both geometries are simulated with two different numerical models, which shall be compared as well. The highest accuracy is expected from expensive unsteady RANS (uRANS) computations of the full propeller geometry rotating at the design speed. In the other case the propeller effect is simulated by an actuator disk (see Fig. 3) to enabled steady RANS computations. The question should therefore be answered as to whether this inexpensive method that was used in numerous previous studies delivers reasonable results to assess the aerodynamic performance of conventional and unconventional propeller integration.

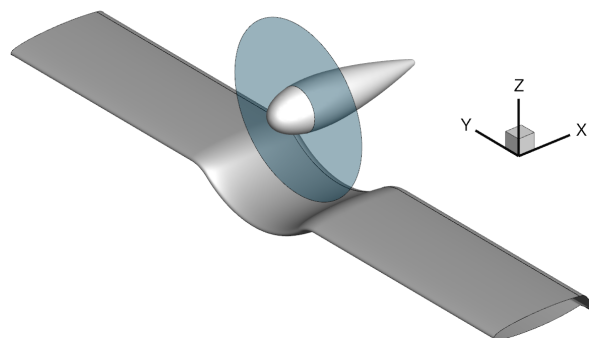


Figure 3. Actuator disk model (on channel wing).

Identical boundary conditions were prescribed for all above-mentioned test cases. To analyse the integration effects at its extreme case, the takeoff operating point has been selected due to the combination of

high thrust and high lift. At sea-level and a Mach number of $Ma_\infty = 0.172$, corresponding to a Reynolds number of $Re = 17 \cdot 10^6$, an angle of attack of $\alpha = 0^\circ$ has been applied to reach a lift coefficient of $c_l = 3.2$ at the clean wing segment.

B. Wing and Airfoil Geometry

For this basic aerodynamic study, a simplified test case with an unswept, rectangular wing and a propeller with generic nacelle was designed. In order to exclude aspect ratio dependencies and tip vortices, a symmetry condition was applied at both ends of the wing segment. The lateral distance of these boundaries which can be considered as wingspan b was comparatively small with $b = 2s = 5c$ to save computation time. In contrast to previous channel wing concepts⁸, the depth of the channel was reduced to one third of the propeller radius. The annular gap between blade tip and wing surface was kept small (2 % of D_P) to enhance integration effects. The airfoil with its chord length of $c = 3.8$ m is based on the transonic DLR F15 airfoil¹⁰ which has been equipped with a $0.25c$ long (plain) internally blown flap (IBF). In particular, the boundary layer control system works with the Coanda effect by blowing a small jet (nozzle width 0.0625 % of c) over a curved surface. For the flap angle of 45° , a jet momentum coefficient of

$$c_\mu = \frac{V_j \cdot \dot{m}_j}{q_\infty \cdot b \cdot c} = 0.025 \quad (1)$$

was adjusted (j : jet flow) for all test cases to ensure attached flow at optimal efficiency.

C. Propeller model

An existing nine-blade propeller which was originally designed for a similar STOL research project¹¹ was adapted to the present thrust requirements by reducing its diameter from $D_P = 6$ m to $D_P = 5$ m. The shaft speed was increased by the inverse scaling factor to keep a constant blade tip Mach number of $Ma_{tip} = 0.75$. This was important to maintain the aerodynamic and acoustic characteristics of the propeller. The geometry of the slightly swept blades is the result of a two-point design, aiming at high takeoff thrust at low rotation speed (for reduced noise emissions) and high efficiency at cruise.

As mentioned in chapter A, the propeller was either modeled by its actual (moving) geometry or an actuator disc with blade element theory¹². The latter means that the inhomogeneous inflow of an installed propeller is taken into account as the local disk forces are computed iteratively using an aerodynamic database. According to the propeller design, the distribution of blade twist and chord length as well as the lift and drag characteristics were prescribed at discrete radii. While the blade number and rotation speed were specified as constants, the pitch angle was adjusted to achieve the desired shaft power. The resulting values of $\beta_{75} = 29^\circ$ for the tractor configuration and $\beta_{75} = 33.3^\circ$ for the channel wing were used for both steady and unsteady simulations. Besides its requirement for a power balance, the simulated torque leads to a realistic swirl in the propeller slipstream.

D. Computational Domain and Grid

Two different grids were generated for each configuration to allow for the different propeller models. A cylindrical farfield domain with a radius of ten chord lengths was selected in both cases to apply a symmetry condition on the side walls. All wing, blade and nacelle surfaces were assigned a turbulent viscous wall condition. As shown in Tab. 1, individual grids were created depending on the numerical method.

The semi-automatic grid generator *Centaur* was used for the steady simulations due to its actuator disk support and easy use for meshing numerous different geometries rather than its capabilities in the slot region. As for this critical area structured mesh blocks can significantly improve the cell quality, the *Gridgen* software was used for the unsteady meshes. Gridgen uses the “bottom-up” approach which allows for more

Table 1. Mesh parameters for the channel wing depending on the CFD method (similar for tractor).

	Steady simulation	Unsteady simulation
Mesh generator	Centaur (Centaurosoft)	Gridgen (Pointwise)
Propeller model	Actuator disk	Chimera method
Total mesh points	10 M	25 M
Wall cell height	$y^+ \approx 0.2...2$	$y^+ \approx 0.1...2.5$
Jet (slot grid)	Prisms, tetrahedra	Hexahedras

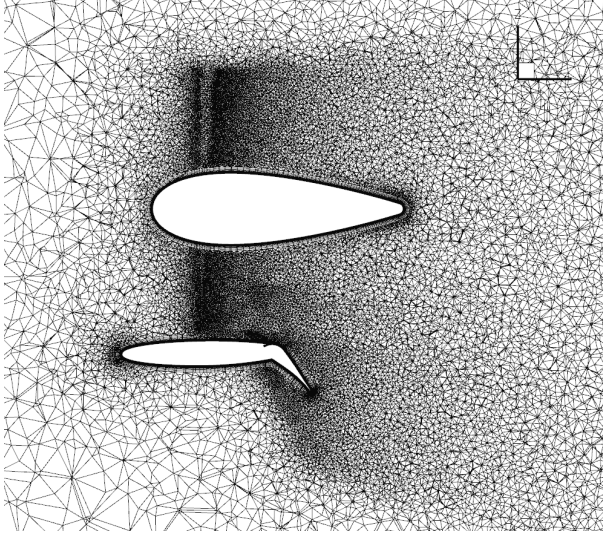


Figure 4. Cross-sectional view of actuator disk mesh for steady simulations.

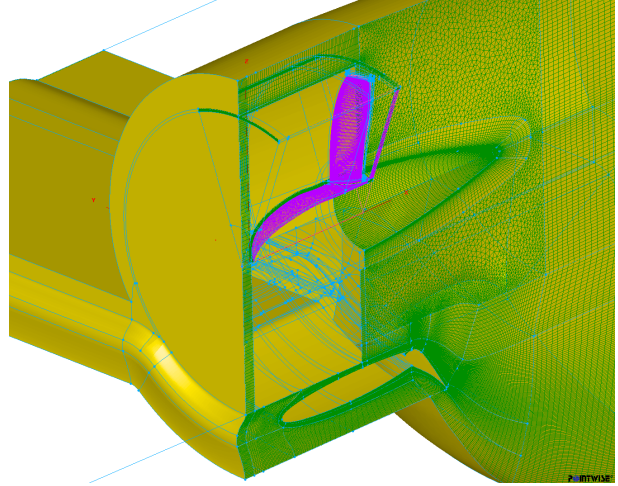


Figure 5. Cross-sectional view of 3D background mesh, containing one blade mesh of the moving block.

control of the grid topology and cell shape. Anyway, the lack of actuator disk support was not an issue for the unsteady simulations as the propeller was modeled by a cylindrical rotating block containing the blades, hub and spinner. An implemented *Chimera* approach was used in the transition zone between the propeller grid and background mesh where an overlap of at least 6 cells was ensured.

In order to further improve the accuracy of the 3D solution, regions of expected high gradients like the propeller slipstream and wake of the flap were refined by means of grid sources (Centaur, cf. Fig. 4) or, respectively, fine structured blocks (Gridgen, cf. Fig. 5). It is evident that such different grids lead to deviations in the prediction accuracy, even at the outer wing segment that is not influenced by the propeller. However, attempts were made to ensure comparable grid resolutions, at least in the near field region around the wing. This is confirmed by the dimensionless height of the wall-nearest cell y^+ which is similar for both meshes (Tab. 1).

E. Numerical Method

All CFD simulations were conducted by using the *DLR TAU code* for solving the RANS equations on the (generally) unstructured grids. Turbulence was modeled by the Spalart-Allmaras one-equation formulation¹³ with a correction for rotational flow¹⁴. While the inviscid fluxes of the Navier Stokes Equations were discretized by a central scheme with scalar dissipation, all viscous fluxes were discretized by a central scheme using a full gradient approach. The influence of laminar boundary layers on the aerodynamic properties was assumed to be negligibly small at $Re = 17 \cdot 10^6$ so that all solid surfaces were treated fully turbulent without transition.

For the steady simulations, a backward Euler implicit time integration scheme was used to achieve quick convergence with CFL numbers around 5. The convergence criterion includes a density residual drop of five orders of magnitude and C_A -oscillations smaller than $\Delta C_A = 1 \cdot 10^{-4}$ which usually took about 50000 iterations from scratch.

In contrast, a Runge-Kutta explicit scheme with CFL numbers of 1 to 1.6 was used for the unsteady computations. Convergence was achieved after 15 (for the tractor configuration) or, respectively, 18 (for the channel wing) propeller revolutions when the lift and drag coefficients were constant (change lower than 0.1 %) during the inner iterations of a time step. The number of time steps for one revolution was varied from 120 (3° pitch) for the first revolutions to 720 (0.5° pitch) for the last two revolutions. At the same time, the number of inner iterations per time step could be reduced from 250 to 50.

III. Results

A. Overall performance

The aerodynamic assessment of the configuration (consisting of the wing segment and the propeller) can be carried out by determining the particular figures of merit, namely the lift-to-drag ratio and the propeller efficiency. As shown for the same takeoff conditions⁷, the climb angle is an aerodynamically and acoustically relevant parameter which depends on the above-mentioned figures of merit. However, to distinguish the effects of mutual influence, the lift, drag, thrust and power coefficients are shown separately in Fig. 6 and Fig. 7.

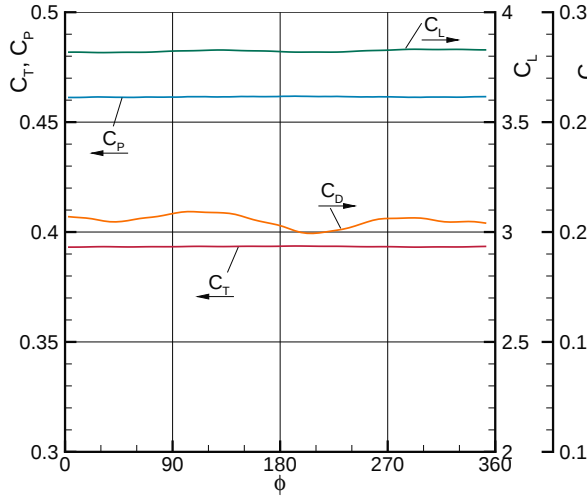


Figure 6. Coefficients of tractor configuration over rotation period.

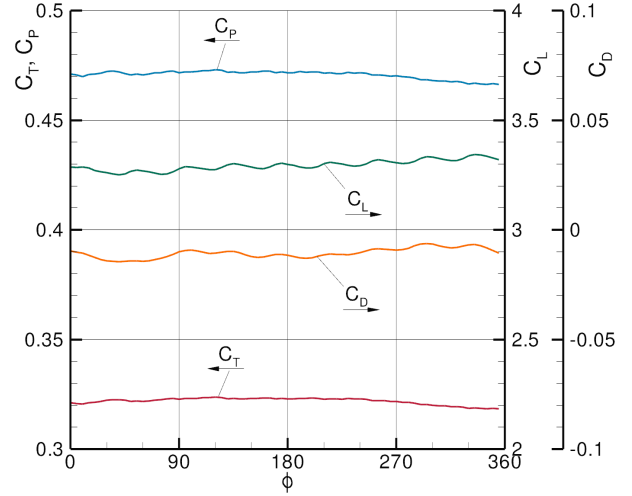


Figure 7. Coefficients of channel wing configuration over rotation period.

The corresponding timeplots could be easily extracted from the unsteady simulations and were evaluated for one propeller revolution, equivalent to a time period of 0.062 s. It was expected that the wing coefficients would reflect the blade pitch of 40° as period while the propeller coefficients would be nearly constant for this high number of blades. This is indeed the case for the tractor configuration (Fig. 6) but not the channel wing (Fig. 7). The latter shows a low-frequency fluctuation with a larger period than one revolution. It is therefore most likely induced by unsteady separations at the wing. In addition to this low frequency noise, a 40° oscillation is clearly visible for both wing coefficients. On the other hand, the lift and in particular the drag of the tractor oscillate at approximately half the rotor frequency. The fluctuation has still a small amplitude compared to the large average of the drag coefficient. The mean values of the figures of merit are

listed in Tab. 2 together with the results of the steady simulations.

Table 2. Mean figures of merit dependent on configuration and computational approach.

		Steady	Unsteady
Tractor	L/D	5.763	6.274
	η_P	0.609	0.614
Channel wing	L/D	9.381	8.844
	η_P	0.491	0.493

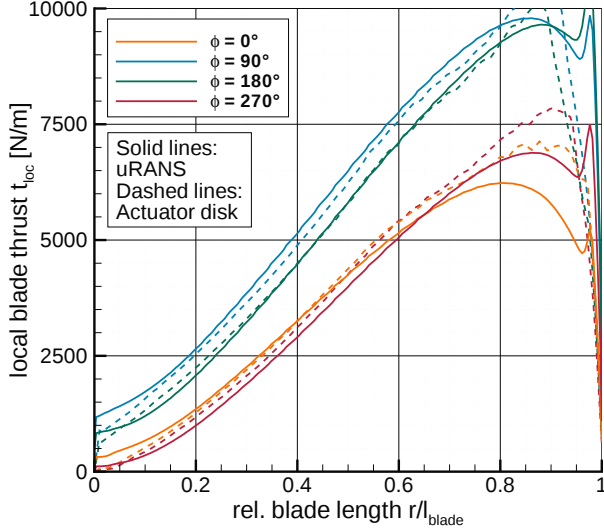


Figure 8. Thrust distribution of tractor propeller blade over rotation angle.

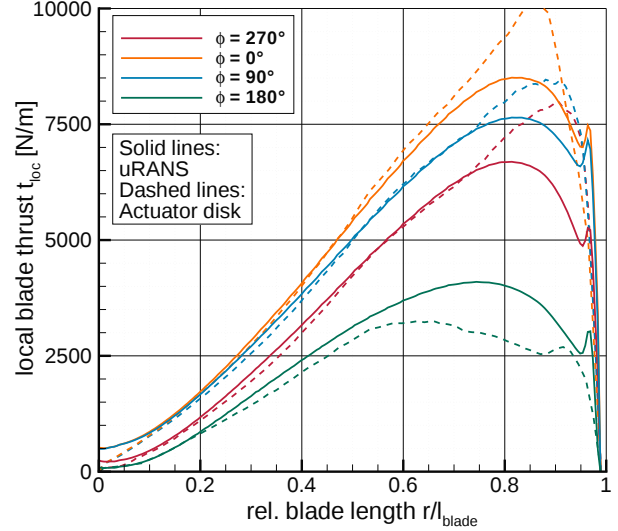


Figure 9. Thrust distribution of over-the-wing propeller blade over rotation angle.

While the propeller efficiency

$$\eta_P = J \frac{C_T}{C_P} \quad (2)$$

with the advance ratio

$$J = \frac{V_\infty}{nD} = 0.72 \quad (3)$$

could be directly computed from the CFD results, the lift-to-drag ratio was evaluated for the overall aircraft and not only for the rectangular wing segment. With the absolute lift and drag coefficients of the aircraft without propeller influence known from the preliminary design, the differences due to thrust were determined by the numerical flow simulations. More precisely, the particular coefficients at the outermost (clean) wing section were subtracted from the total value of the CFD configuration:

$$\Delta C_L = C_L - c_{l, clean} \quad (4)$$

These increments were subsequently added to the absolute (reference) coefficients $C_{L, ref} = 2.79$ and $C_{D, ref} = 0.381$ to determine the lift-to-drag ratio

$$\frac{L}{D} = \frac{C_{L, ref} + \Delta C_L}{C_{D, ref} + \Delta C_D} \quad (5)$$

The agreement between the actuator disk computations and high-fidelity unsteady simulations is quite good, especially for the tractor configuration. It is worth mentioning that the general trend and the major

differences between these two configurations have been already discussed based on steady CFD results. Considering the computation time and costs, this was the only reasonable method for geometry variations⁹ and evaluation of characteristics (regarding thrust, Mach number and angle of attack dependencies)¹⁵.

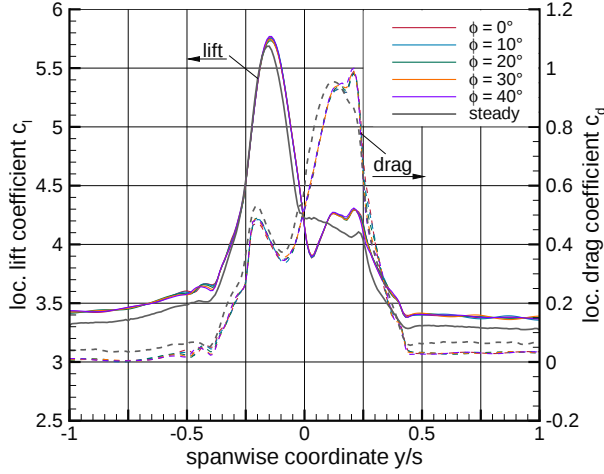


Figure 10. Spanwise lift and drag distributions of the wing with tractor propeller

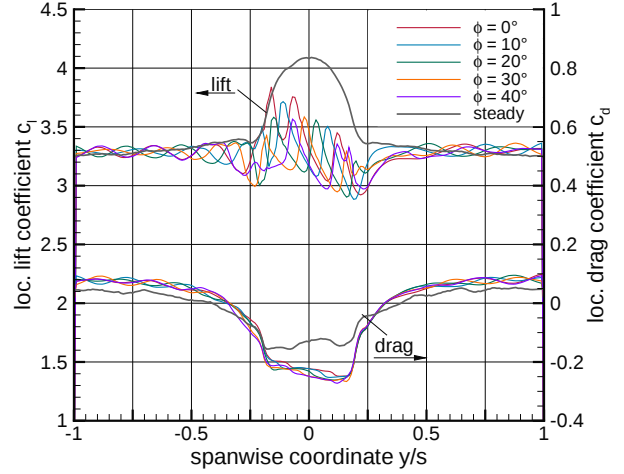


Figure 11. Spanwise lift and drag distributions of the channel wing

B. Propeller aerodynamics

While the overall thrust and shaft power of the propeller are almost time invariant, the forces of every single blade are indeed oscillating during one revolution. This is an expected and known effect of inhomogeneous inflow conditions (flow angle and velocity) as present for both configurations, albeit much stronger for the channel wing. It is also captured by an active actuator disk (based on blade element theory) as used in the steady simulations. Figure 8 shows the local thrust distribution of one blade of the tractor propeller for 4 positions with 90° interval (0° equals the 12 o'clock position, cf. Fig. 12) and compares them to the corresponding sections of the actuator disk. Both simulations predict the maximum thrust between the 90° and 180° position and a minimum (approx. 1/3 lower thrust) on the opposite side. This diagonal shift has been already described in previous work⁷ as a combined effect of inflow velocity and inflow angle gradients. It is, however, remarkable that the actuator disk distribution is in good agreement with the unsteady simulation of the full propeller blade geometry. The only serious deviation can be found near the blade tip which is dominated by its wake vortex. Note that the actuator disk uses aerodynamic data obtained by Euler computations of the discrete airfoil sections which cannot take into account three-dimensional features like blade tip vortices.

Similar agreement between the two simulation techniques is achieved for the channel wing propeller, see Fig. 9. However, the inhomogeneous inflow at this configuration is dominated by a strong vertical gradient of the velocity magnitude with maximum values in proximity to the wing surface. The minimum thrust is consequently generated at the lower (6 o'clock) position. In fact, the relative thrust at the representative radius $r/l_{blade} = 0.8$ oscillates between approximately 50% and 100% (12 o'clock position) due to the distance to the wing.

C. Wing aerodynamics

The spanwise distributions of the lift and drag coefficients of the wing are shown in Fig. 10 for the tractor configuration. It is obvious that, at least for takeoff conditions, the propeller has a strong influence

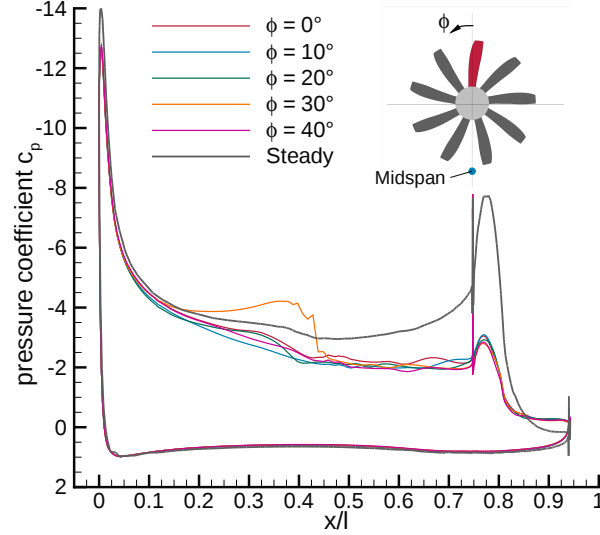
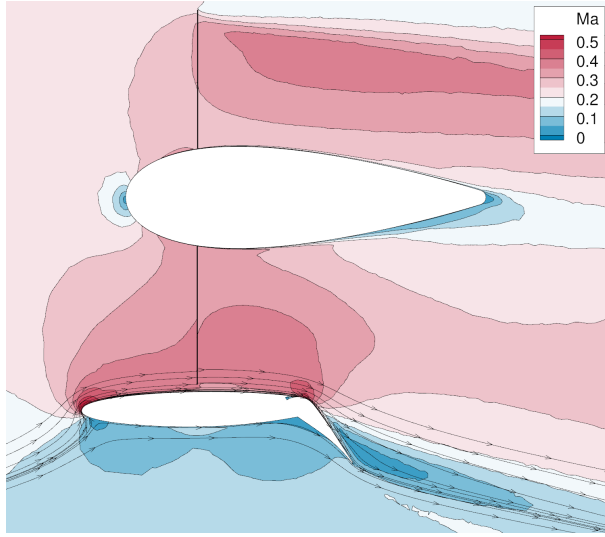


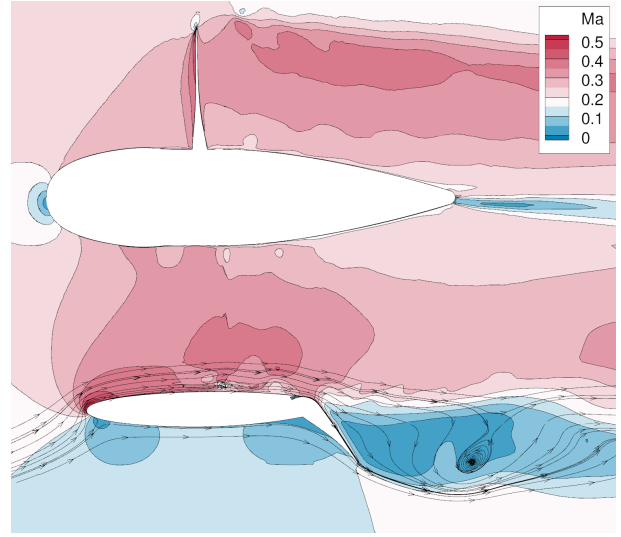
Figure 12. Unsteady pressure distributions of the channel wing at midspan.

on the wing. It is known that two major effects change the pressure distribution and therefore the lift and drag¹⁶: the first one is the asymmetric up- and downwash due to the swirl in the slipstream; the second one is the symmetric increase of the dynamic pressure (or flow velocity) behind the propeller. For example, the downwash induces a negative angle of attack which leads to locally increased c_d and decreased c_l . The overall lift is nevertheless higher compared to the outer wing section due to the significantly larger dynamic pressure. At takeoff, this effect is much larger than for cruise conditions¹⁷ where it can be often neglected. The agreement between steady and unsteady simulation is particularly good in the propeller region while the uRANS computations predict a higher lift and lower drag at the outer wing segments. It is remarkable that both distributions are almost time invariant and not dependent on the propeller blade position. This is not the case for the channel wing where the mutual interaction is of completely different nature, see Fig. 11. The lift and drag distributions of the steady actuator disk simulations are almost symmetric with higher lift and lower drag in the channel below the propeller when compared to the outer (clean) wing. In contrast, the unsteady results reflect the pressure field of every single blade. This leads to sinusoidal distributions along the span whose phase varies with the rotation angle. It is obvious that the maximum amplitude, at least for the lift coefficient, is reached in the channel where the distance between blade and wing is minimal. However, the mean lift is asymmetrically distributed and significantly smaller than predicted by the steady simulation. At the same time, the mean drag in the channel is even smaller, leading to a significant amount of induced thrust. This indicates a weakened suction peak on the coanda surface of the flap that normally contributes to lift as well as drag³.

The pressure distribution of the wing segment at midspan, cf. Fig. 12, confirms the above mentioned hypothesis and shows a distinct separation on the flap. In contrast, the pressure distribution which was obtained by the steady simulation does not give any evidence of flow separations but a large rear suction peak. It is remarkable that c_p varies only in a small area below the propeller when the blade is passing by (shown for different rotation angles) while the flap is continuously separated. Figure 13 shows the differences in the flowfield at midspan (propeller axis) and reveals that, for unsteady flow, the Coanda jet is still attached at the entire flap, whereas the outer flow separates intermittently. As a consequence, almost no rear suction peak is present which reflects the findings in Fig. 12. An analysis of the eddy viscosity in the wake (Fig. 14) illustrates that the blade tip vortices are most likely interacting with the boundary layer on the upper surface of the wing by inducing instabilities and decreasing its momentum. The subsequent Coanda jet is not strong

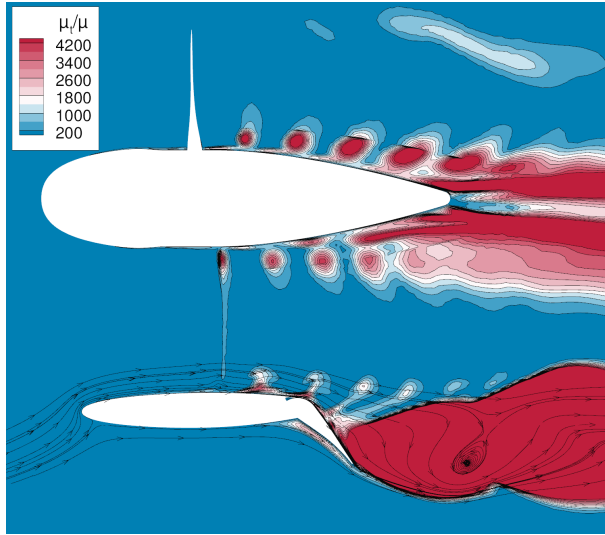


(a) Steady simulation.

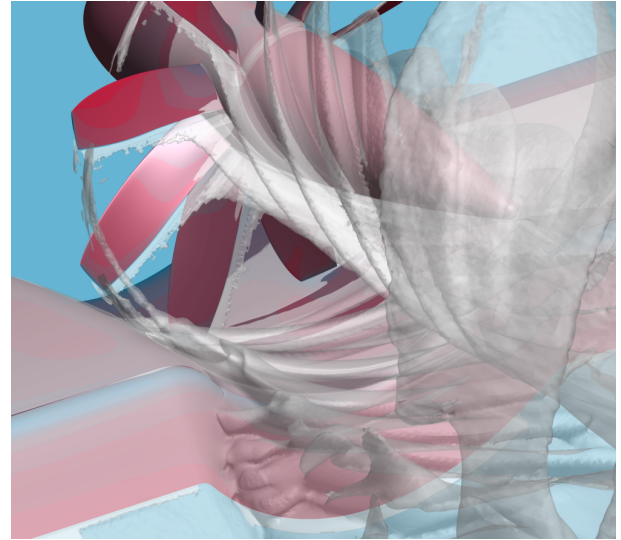


(b) Unsteady simulation (snapshot for $\phi = 0^\circ$).

Figure 13. Flowfield (Mach number and streamlines) of the channel wing at midspan.



(a) Midspan cross section.



(b) Iso-surface in 3D field.

Figure 14. Eddy viscosity ratio in the flowfield of the channel wing (unsteady).

and thick enough to restore the momentum of the weakened boundary layer for the forthcoming high turning around the flap. It is evident that this effect could not be predicted by steady actuator disk simulations. As already indicated by the time series in Fig. 7, the blade tip vortices impinge on the wing surface at the blade passing frequency while the extent of the actual separation (deep red area above the flap) may fluctuate with a considerably lower frequency.

IV. Conclusions

Numerical flow simulations have been conducted at takeoff conditions for two different propeller-wing configurations with internally blown flap at $Ma_\infty = 0.172$ and $Re = 17 \cdot 10^6$. Not only the types, a conven-

tional tractor configuration and a channel wing (over-the-wing propeller), but also two numerical approaches were compared. One of them is based on steady RANS simulations using an actuator disk which can react on the inflow conditions, while the other simulates the full propeller geometry with moving blades by unsteady RANS. Despite the simplifications in conjunction with the first-mentioned method, the major features as well as differences of the two configurations are predicted satisfactorily:

- The lift increment due to the tractor propeller is significantly larger than for the over-the-wing installation
- While the pressure drag is strongly increased in the slipstream of the tractor propeller, it is considerably decreased at the channel wing.
- The thrust of the over-the wing propeller is shifted from the wing to the upper position, leading to a 20 per cent loss of net thrust or propeller efficiency, respectively.

However, the unsteady simulation of the full geometry reveals some new details of the flow:

- The blade tip vortex alters the thrust distribution in the region of influence.
- The same vortex interacts with the boundary layer of the channel wing which leads to detached flow at the flap. As a consequence, no suction peak emerges on the Coanda surface which is why the lift augmentation is negligibly small.
- The pressure field of each propeller blade is propagated along the entire wing span, causing unsteady sinusoidal lift and drag distributions.
- The mean lift distribution of the channel wing is asymmetric with a local maximum not at midspan but below the upward-moving blade.

In summary, steady RANS simulations with actuator disk, on condition it works with blade element theory using reasonable aerodynamic characteristics, are feasible when aiming only at major integration effects. Although some flow details and a large separation are only predicted by unsteady simulations, the most important figures of merit, namely the lift-to-drag ratio and the propeller efficiency are in acceptable agreement.

V. Acknowledgements

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