Project ForMEx - A new CFD Approach for transposition of Wind Tunnel data towards Flight Conditions

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Summary

In this paper a new approach of CFD supported wind tunnel testing is presented based on investigations of the DLR project ForMEx [1] - [3]. The numerical simulation and respectively the analysis of the wind tunnel experiment considering all geometrical and aerodynamic conditions show improvements of today's wind tunnel testing techniques which is outlined in this paper for the wind tunnel DNW-NWB.

1 Introduction

For the design of new aircraft configurations the wind tunnel experiment still represents an indispensable tool in order to predict the aerodynamic performance of single aircraft components as well as the overall configuration and respectively to validate numerical procedures. In this context extrapolation of the wind tunnel tests to free flight conditions within this process contains certain inaccuracies.

The wind tunnel flow does not correspond to the free flight because of wall and model mounting effects. In order to minimize these influences to a large extent, data corrections of the wind tunnel tests are performed, which up to now are based on simple procedures and hand book methods. The wind tunnel measurements usually are performed with smaller models compared to the original, and the extrapolation to real conditions is done by each aircraft company using their own extrapolation procedures. Aerodynamic performance data resulting from the wind tunnel experiment therefore are still affected by certain systematic errors.

During the last years advanced modern procedures for CFD flow simulation have been further developed. In particular by the use of unstructured codes for the flow simulation around complex configurations and geometries also complete wind tunnel flows can now be handled with the required accuracy and justified effort. Thus the critical examination of existing wind tunnel correction procedures and their improvement is made possible, leading to more reliable procedures for the prediction and extrapolation of the wind tunnel experiment to free flight. Within the DLR project ForMEx the numerical simulation and respectively the analysis of the wind tunnel experiment considering all geometrical and aerodynamic conditions is performed in order to improve the wind tunnel testing technique described above.

In the process also model and model mounting deformations are considered using flow/structure coupling methods. From the deviations detected by careful comparisons of the experimental data with the results of the numerical simulation of the experiment correction rules will be derived. On the one hand they will help to identify the limits of existing wind tunnel correction methods and possibly will lead to certain improvements, on the other hand they also will serve for validation and improvement of numerical methods.

Based on the ForMEx project work the present paper describes the CFD potentials to support wind tunnel testing in the low speed wind tunnel DNW-NWB with a transport aircraft half model mounted in the test section.

2 Numerical Method

The solution of the Reynolds-averaged Navier-Stokes equations (RANS) is carried out using the hybrid unstructured DLR TAU code [4]. For the closure of the Reynolds-averaged equations the k-ω-SST turbulence model of Menter is used, which combines robustness with the applicability for partly detached flows. Due to the low Mach numbers and the resulting stiffness of the RANS equations, low Mach number preconditioning is used. Finally, the central JST-scheme in combination with 80% matrix dissipation assures numerical flow solutions with low numerical dissipation. To increase the convergence, an implicit time-integration (LU-SGS) is implemented in the TAU code.

3 Results

Strongly coupled with the experimental simulation of high lift configurations in the wind tunnel is the so called half model technique. It results from the demand of the same Reynolds number in free flight and wind tunnel experiment to get the flight physics as real as possible in the wind tunnel experiment.

On this point the half model technique is introduced using the assumption of a symmetrical flow around the aircraft by cutting it on the symmetry axis along the fuselage and measure this configuration in the wind tunnel. Using this technique the model size can be doubled without changing the test section and getting a doubled Reynolds number holding all other parameters constant compared to the full span.

A reduction in the quality of the measurements results from the increased wind tunnel interference resulting from the model volume and the mounting of the model on the tunnel floor or ceiling, in which the model is partially covered by the tunnel wall boundary layer. To reduce this influence and to reduce the disturbance of the symmetrical flow the fuselage is often mounted on a cylindrical extension of its symmetry cut called peniche or stand-off.

But even using a peniche a completely symmetrical flow in the symmetry plane cannot be achieved, due to the horse-shoe vortex between peniche an tunnel wall. Because of this, the unsymmetrical flow cannot be eliminated by changing the peniche height and this behaviour always leads to a difference between a half model compared to the full span model measurement. Only the displacement of the peniche will vary in case of a peniche height change.

3.1 Model and Wind Tunnel

In this paper the ALVAST transport aircraft geometry in landing configuration is considered in the wind tunnel DNW-NWB. The ALVAST model is a generic configuration of a modern, twin-engine transport aircraft comparable with an AIRBUS A320 in scale 1:10. Beside the wing this landing configuration consists of a single slat and a single slotted flap which is split into an inner and outer part [5].

The low speed wind tunnel in Braunschweig (DNW-NWB) is an atmospheric wind tunnel of Göttinger design with a closed loop. The construction of the tunnel was finalized 1960 and the tunnel is integrated since 1996 in the German-Netherland wind tunnels (DNW). The test section has the size of 3.25 m x 2.8 m and reaches a flow speed of 90 m/s at an maximum drive-power of 1.4 MW.

3.2 Numerical Simulation of a Wind Tunnel

The peniche plays an important role for the half model technique and therefore it also has been considered and simulated in the investigation described in this paper. On the peniche as well as on the fuselage the boundary layer of the model and the tunnel wall interacts. Therefore the tunnel wall on which the model was mounted has to be simulated viscid. The remaining walls can be treated inviscid to reduce the numerical effort. However with an increasing angle of attack and thus blockage a wind tunnel model has a remarkable influence on the boundary layer of the tunnel walls. Because of this all tunnel walls are treated viscous in this simulation.

In principle the numerical simulation of a wind tunnel can include the complete tunnel with test section, diffuser, direction change, drive, settling chamber and nozzle. Indeed this would be an additional effort to simulate the intrinsic flow in the test section. Therefore it would be sufficient to simulate only the test section with an in- and outflow. But the shape of the boundary layer on the tunnel walls at the inflow is not known. By adding the nozzle and the settling-chamber to the simulated domain this problem can be solved because the flow straighteners in front of the settling chamber remove the boundary layer and for this reason the flow topology can be handled numerically at this station.

The boundary conditions for the simulation of the in- and outflow serve at the same time for the control of the flow speed in the numerical wind tunnel. A detailed description can be found in [6] and shall not be repeated here.

To change the angle of attack of the model in the wind tunnel during the experiment a turntable on the tunnel floor is used. To simulate this numerically in the current investigation the Chimera technique is used. Therefore the tunnel is meshed without the model, afterwards the volume is cut out in which the configuration is rotated at different angles of attack. In this volume an second grid is inserted including the model. To assure the communication between both grids on the boundaries an overlap was used [7]. The final grid consists of about $21 \cdot 10^6$ points.

Three configurations have been used to identify the wind tunnel influence on the flow for a high lift configuration under consideration of the half model technique. In Table 1 these configurations are listed. By simulating with and without peniche and accordingly with wind tunnel and free flight a breakdown in the influence of a finite test section (wind tunnel influence) and the half model technique (peniche influence) can be done.

The simulations were accomplished using the following freestream conditions: $V = 60\,m/s,\ Re = 1.435 \cdot 10^6$ with a reference length of $l = 0.41\,m$.

Further investigations have been carried out on the peniche gap, peniche height and influence of the wing-fuselage junction on maximum lift. This additional investigations are not shown in this paper, details can also be found in [6].

3.3 Peniche and Wind Tunnel Effect

To determine the wind tunnel influence and at the same time to distinguish it from the peniche influence in this section the so called ”difference pictures” are used. In this pictures the flow variables angle of attack, lengthwise and crossflow velocities of two configurations are shown in cuts perpendicular to the freestream and to the wing span direction. Thereby the values of the first solution are deducted from the solution of the second configuration. Thus these ”difference pictures” (Fig. 1 and Fig. 2) show the changes between two configurations which otherwise are difficult to detect. Comparing the local angle of attack for configurations with and without a peniche in the wind tunnel (conf. A&B) it can be found Fig. (1a) that the peniche leads to an increased local angle of attack on the inboard wing of about $\Delta\alpha \approx 1^o$ whereas the outboard wing is not influenced. The influence of the tunnel walls in contrast (conf. B&C, Fig. 1b) results in an additional angle of attack on the complete wing span of about $\Delta\alpha \approx 0.5^o$. The superposition of both effects can be found accordingly between the configuration A&C, Fig. 1c.

The reason for this peniche effect is by the additional blocking of the peniche in the flow field. This leads to an additional displacement of the flow leading to an increased flow speed and local angle of attack on the model. With increasing angle of attack this effect increases. Further on with increasing distance (e.g. along the wing span) this peniche effect decays. Around the fuselage an interplay between the peniche and wind tunnel effect can be found. Considering Fig. 2a the main influence of the angle of attack can be found in proximity of the fuselage especially in regions where the horse-shoe vortex is located. The wind tunnel effect in contrast leads to an increased angle of attack in front of the model of about $\Delta\alpha \approx 1^o$ and behind the configuration to an additional value of about $\Delta\alpha \approx 4^o$ compared to the free flight, Fig. 2b. The reason is the downwash of the wing, which cannot spread out downwards because of the wind tunnel wall. Again these effects are superimposed on configuration A&C.

Concerning the crossflow velocity the peniche influence decelerates the flow above and accelerates the flow below the fuselage, in both cases of about $\Delta V = \pm 1\ m/s$, whereas the wind tunnel influence has no effect (see Fig. 1). Because of the spatial reduction of the peniche influence the crossflow velocity is mainly changed on the inboard wing. The lengthwise velocity is decelerated because of the peniche influence in front of the model and accelerated above the model because of the wind tunnel effect. These wind tunnel effects lead to a nearly constant acceleration of about $\Delta u = \pm 0.5\ m/s$ on the complete wing span superimposed by the peniche influence on the inboard wing. In the same manner as before the effects are superimposed in configuration A&C.

Concluding the peniche effect, the flow around the fuselage and the flow deflection are increased leading to an increased flow velocity and local angle of attack on the inboard wing. The strength of the peniche effect is therefore a function of the angle of attack and changes the lift rise, compare Fig. 3. Further on the configuration without peniche has a reduced lift coefficient of 2.6% also. The peniche effect can be found at all angles of attack because the displacement of the peniche always takes place.

From the lift curves a change in the maximum angle of attack can be found with and without peniche. With peniche the maximum angle of attack is at $\alpha = 15^o$ whereas without peniche at $\alpha = 15.5^o$. In this case the additional load on the inboard wing due to the peniche reduces the maximum possible angle of attack. If this behaviour is triggered by the peniche it is mainly decided were the flow separates, first on the inboard or outboard wing. In the first case the peniche increases the load on the inboard wing and intensifies the lift breakdown there. Using half model measurements this effect must be always keept in mind.

Comparing the lift curves of configuration A&C (Fig. 3) it is clearly visible the one got from the wind tunnel simulation is shifted above the one of the free flight. The reason is the wind tunnel effect which leads to an increasing angle of attack and flow velocity. The peniche effect leads simultaniously to an increased gradient of the lift curve compared with the free flight.

3.4 Wind Tunnel Correction

In Fig. 3 the corrected and uncorrected lift curves from the measurement in the wind tunnel DNW-NWB are shown with the corresponding numerical simulations in the tunnel and the free flight. Configuration A corresponds to the uncorrected measurement, configuration C the corrected one. The corresponding curves of the measurement and the simulation show a good agreement in the linear range.

To get a more detailed assessment of the wind tunnel correction without regarding a measurement and with removing possible measurement errors the lift curves of the simulation in the wind tunnel are corrected with wind tunnel correction and compared to the lift curves of the free flight. The wind tunnel correction is well defined, if this corrected results correlate with free flight simulations. The results are shown in Fig. 4 for configuration A (in wind tunnel), uncorrected and corrected, and for comparison configuration C (in free flight). The corrected lift curve of the configuration matches the lift curve of configuration C with a slightly higher gradient and a little bit increased level. The corrected lift curve of configuration B has a slightly reduced gradient and a lower level compared with the free flight. Without peniche there is no additional displacement which can compensate the boundary layer of the tunnel wall. On the other hand with peniche the displacement increases with increasing angle of attack and leads to an only point-wise matching of the corrected wind tunnel measurement and the free flight values as a function of the peniche height.

Overall the used wind tunnel correction shows a good agreement in the linear range of the lift curve with the numerical simulations. However the peniche effect is not corrected, especially in its spanwise variation. This leads to spanwise differences in the pressure distributions (not shown here, compare [5]). Furthermore caused by the variation of the displacement with the angle of attack the wind tunnel correction can only be applied for one angle of attack.

4 Conclusion

A new approach of CFD supported wind tunnel testing is presented in the present paper based on investigations of the DLR project ForMEx. ForMEx is aimed at more accurate wind tunnel correction methods and improved extrapolation to free flight conditions by using CFD techniques for the complete wind tunnel flow analysis. The results show that the numerical simulation is able to identify the limits of existing wind tunnel correction methods and thus can be used as basis to improve today's wind tunnel testing techniques outlined here for the wind tunnel DNW-NWB.

To achieve these results the test section including the nozzle together with the ALVAST high lift configuration as half model and the ALVAST full span model in free flight have been simulated in order to investigate the half model (peniche) effect as well as the wind tunnel influence. From this investigation the following statements can be outlined: The impact of wind tunnel on the flow around a half model can be divided in a peniche and a wind tunnel influence. The local angle of attack and the flow velocity is increased mainly in the inboard part of the wing due to the peniche influence. The wind tunnel wall effect also has an influence on the inboard wing, but with a smaller value. Therefore the wind tunnel influence can be mainly found at outboard wing parts whereas its effect is present over the complete cross section. When reducing the angle of attack of the model the corresponding effects also decrease.

References

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configuration	with peniche	without peniche	wind tunnel	free flight
A	o		o	
B		o	o	
C		o		o

Table 1 Investigated Configurations

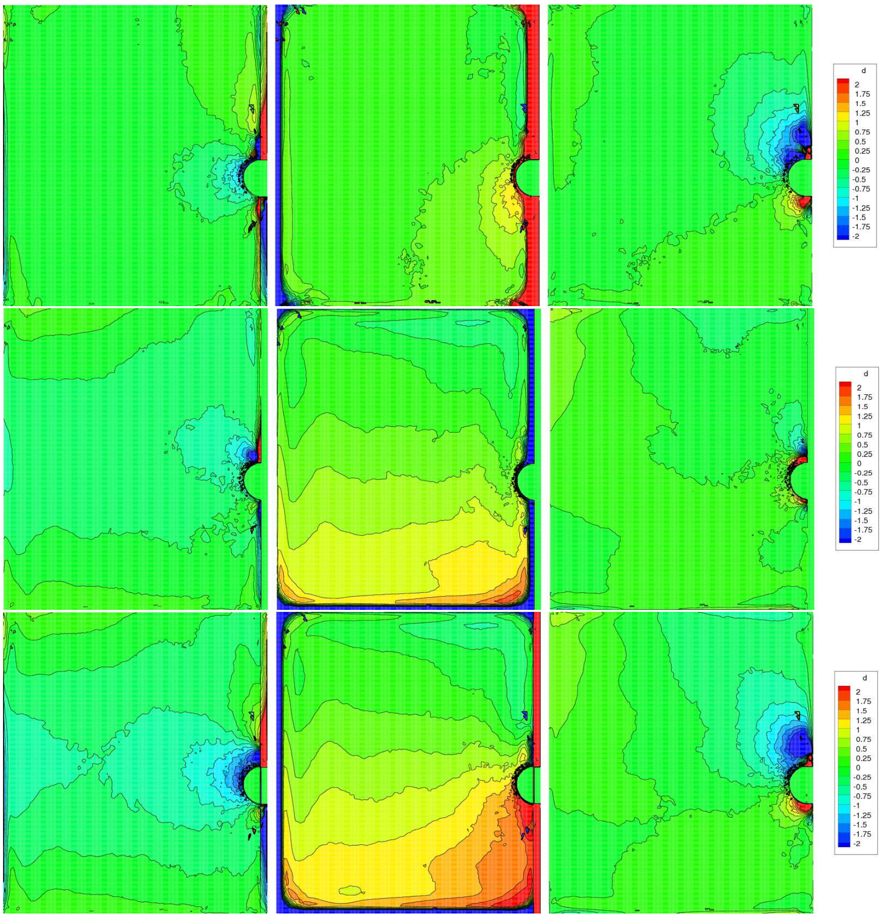


Figure 1 Difference pictures of (left to right): angle of attack, crossflow velocity in x- and z- direction. First row (a): config. A&B, second row (b): config B&C, (c): config. A&C.Cut through the test section in flow normal direction in front of the wing.

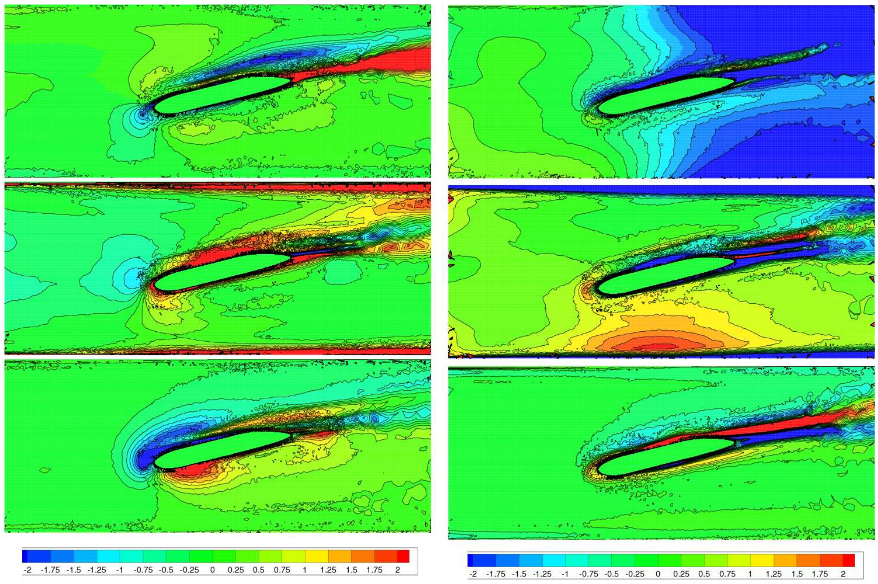
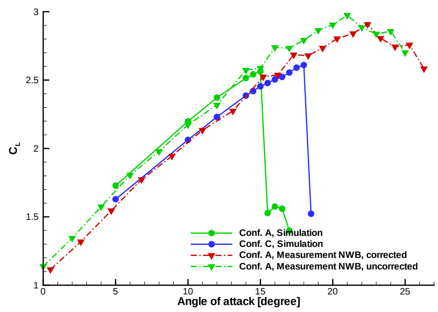


Figure 2 Difference pictures of angle of attack (top), crossflow velocity x- (middle) and z (bottom), left: (a) config. A&B, right: (b) config. B&C. Cut through the test section in flow direction at the peniche.



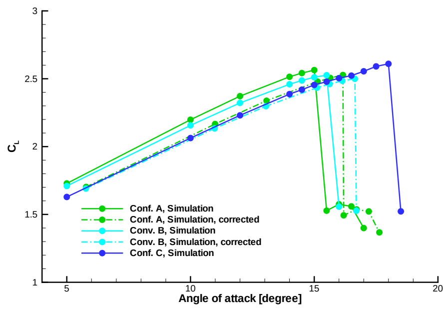


Figure 3 Lift curves of config. A with and without wind tunnel correction to free flight, comparison with free flight simulation C.

Figure 4 Lift curves of config. A&B with and without wind tunnel correction to free flight, comparison with free flight simulation.