HICON AERODYNAMICS - HIGH LIFT AERODYNAMIC DESIGN FOR THE FUTURE

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Abstract

An overview of the current Airbus high-lift design process is presented, including the use of 3D computational fluid dynamics (CFD), high Reynolds number testing and the establishment of aeroacoustic design guidelines. One of the aims of current research activities performed within the HICON project is to gain valuable experience within these fields.

An example of ongoing work in this area is presented via the aerodynamic design and optimization of a dropped hinge flap. Dropped hinge flap setting variations have been performed with 2D, 2.5D and 3D CFD methods. The results have been compared to wind tunnel tests performed under low Reynolds number conditions. Results to date suggest a good comparison between 2.5D and 3D CFD results (at flight Reynolds number). The trends identified with 2.5D and 3D CFD have not been seen in the low Reynolds number wind tunnel testing. Ongoing work aims to identify the reasons for these differences.

1 Introduction

The demands on the high-lift systems of future civil aircraft are numerous and challenging, for example reduced noise emissions, increased safety, reduced weight and reduced manufacturing and maintenance costs. Reduced noise emissions in itself is a serious challenge, including efforts to reduce both the airframe noise of high-lift configurations and to use different approach and landing procedures (e.g. steep approach) for the reduction of noise-effected areas on the ground. All these demands will have an influence on the design and layout of future high-lift systems, and are likely to cause a gradual change away from the high-lift configurations seen on most civil aircraft today towards more, at least from today's perspective, innovative high-lift solutions.

The research project HICON (New HIgh-lift CONfigurations) is the major forum within which the Airbus aerodynamics department is investigating innovative high-lift configurations suitable for future civil aircraft. HiCon is major part of the lead concept IHK (a German acronym for Innovative High-Lift Configurations) which is running in the frame of the third National German Aviation Research Programme (LuFo III) and is funded by the German Ministry for Economics and Labour.

The HICON project is made up of two phases, the first being the multidisciplinary investigation of various alternative high-lift devices (the systems and structural analysis is performed within the sister project HISYS), the second phase commences with the selection of a target aircraft configuration and requirements which will be subsequently used for the integration of suitable innovative high-lift devices from phase one of the project. This target aircraft will then be analysed on an aircraft level (including aerodynamics, systems, structures, flight mechanics, noise) to provide a complete assessment of the new configuration.

2 Airbus High-Lift Wing Design Process

The maximum lift of a well-designed high-lift profile is always limited by the onset of flow separation on the main wing or the leading edge device. However, on a realistic 3D wing in most cases local disturbances cause the maximum lift limiting separation even before the maximum lift capability of the wing profiles is reached (e.g. disturbances originating from the engine/pylon region). These 3D effects provide a challenge in the design of a high-lift system, especially for theoretical methods used to predict high-lift performance during the design stage.

2.1 Geometry Design

Based on the cruise wing geometry the high-lift wing is designed for meeting the low speed performance requirements. The geometric design process is conducted with parametric “knowledge based engineering” 3D design tools, based on a CatiaV5 platform. A key benefit is knowledge capturing via parameterization, which allows a far-reaching optimization of the aerodynamic design of the high-lift devices highly independent of the detailed boundary conditions, such as the cruise wing profiles or specific systems features. When optimizing the overall solution in the multidisciplinary design process the high-lift solution can be mapped onto the new constraints, maintaining a significant part of the “know-how” of the previous design step. As a further benefit a direct on-line coupling of quick computational fluid dynamic (CFD) analysis methods is given to provide direct-coupled assessment of each design step.

2.2 Aerodynamic Analysis

At the Airbus aerodynamic design department a modern CFD infrastructure was established for the task of the A380 high-lift wing design. The principle for CFD-based design is the use and combination of methods with complexity and expense appropriate to the momentary design task in a 'chain of methods'.

In the early stages of the high-lift wing design, 2D-calculations via a panel method for section design are complemented with quasi-3D calculations (coupling of a 2D-method with a lifting surface method) for assessment of the complete wing performance. As the design matures 2D Navier-Stokes methods are heavily used before a full analysis of the complete 3D high-lift configuration (including engines, pylons, wing tip devices etc.) via 3D Navier-Stokes is performed (using the DLR *TAU*-code), as shown in Fig. 1. This level of analysis is currently available primarily due to the improvements in the recent years of the available computing power which leads to reasonable turn-around times (with respect to the design cycle) for such complex 3D computations.

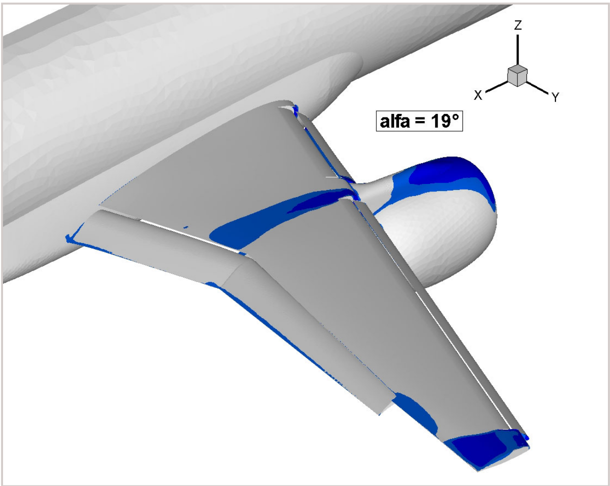

Fig. 1. 3D CFD analysis of a high-lift configuration, the blue areas indicate regions of separated flow.

Besides the CFD methods, wind tunnel experiments are of critical importance to assess the performance characteristics of the theoretically designed high-lift wings. These experiments are also crucial for the final configuration selection and for aerodynamic data production.

For the purpose of high-lift wing design at Airbus several wind tunnels are used. The Airbus low speed wind tunnels in Bremen/Germany and in Filton/UK serve for configuration evaluation and selection. The high-lift configuration can be tested for configuration design development in Bremen including powered turbine or propeller simulation with a half model, while in Filton the assessment of the configuration with a complete model for handling quality issues is conducted. In the German-Dutch wind tunnel DNW tests are performed with a large-scale complete model. Powered turbine simulation is also possible as well as tests with empennage and tests under sideslip conditions and in ground effect.

The flow physics, especially for high-lift configurations, is very sensitive to the Reynolds-number (the flow similarity parameter of importance). As a result further experiments have to be conducted for verification tasks at high Reynolds-number conditions. For those tasks pressurized (e.g. Onera F1) or pressurized and cryogenic wind tunnels (ETW) are used.

2.3 Aeroacoustic Analysis

A relatively new field within the high-lift design process is aeroacoustics. Airbus is including information from computational aeroacoustic (CAA) methods and appropriate wind tunnel tests in closed test sections right from the initial design activities on, in order to obtain as early as possible information about the noise generation process and perturbation dynamics in the vicinity of a wing in high-lift configuration.

Significant effort has been applied to this field in recent years, mainly via research and technology programs such as HICON [1]. From this work a number of significant high-lift design guidelines have been established.

Apart from low source noise, a good aerodynamic high-lift performance can contribute significantly to a low noise aircraft. This is caused by the fact that the noise generated by the wing is proportional to the flow velocity to the mth power, with ($4.5<m<6$). Thus from an aeroacoustic point of view it can be concluded, that for a low noise landing, a good high-lift performance allowing for a low approach velocity is of great importance.

For the leading edge high-lift system it can be said, that a slightly lower maximum lift performance can be accepted if this results in significant improvements of the source noise creation, as the leading edge is the main noise source during approach.

Due to the logarithmic characteristic of acoustics, a noise reduction of the noise dominating leading edge system directly affects the total noise level, while the same noise reduction of the trailing edge system is of lower order in respect to the overall noise level.

Although source noise of the trailing edge devices is by far lower compared to the noise caused by the leading edge (and thus does hardly directly effect the overall noise), the design of the trailing edge can indirectly contribute to a lower total noise level, even if its (i.e. the trailing edges) source noise increases.

Through a combination of a higher performance trailing edge system (even if it generates more source noise) with a lower performance leading edge system (generating less source noise), the maximum lift coefficient can be kept unchanged, while the total noise generation is greatly reduced. This suggests using gapless leading edge devices as a design option for low-noise high-lift systems.

Regarding the take-off condition, the high-lift performance can also contribute to a lower noise level. This is because with a higher lift-to-drag ratio, two options for a lower noise level arise: Firstly, the altitude over and thus the distance to the certification microphone is higher, or secondly, for the same altitude at the certification point, the thrust setting for sustaining the 4% climb angle can be lowered, so that less noise is generated by the engines.

3 HICON Aerodynamic Design

One of the major goals of high-lift research activities within Airbus is to continually improve the methods and processes used in the aerodynamic design process. These improvements are not possible during the aircraft development phase itself and hence HICON forms an invaluable platform on which these improvements can be conducted.

The continuous desire to increase design efficiency and reduce design cycle times has led to a gradual increase in the use of CFD methods for predictive purposes. Parallel to this, the development and validation of cryogenic wind tunnel testing facilities such as the ETW in Cologne, Germany, has provided aerodynamicists with a powerful (and expensive) tool for testing high-lift designs at flight Reynolds number during the design process. Such a facility allows the high-lift design to be optimized for flight-conditions well before flight testing commences.

The logical continuation of this trend leads to a close coupling between high-lift design and validation via 3D CFD methods with flight Reynolds-number testing at cryogenic conditions. This approach is investigated within the HICON project, and is in contrast to design methods used in the past, which relied extensively on experimental testing at relatively low Reynolds number conditions (1-3 Million). One of the major challenges in pursuing a new, or adapted, design process is to obtain an appropriate level of experience in order to be confident that the process is robust. This includes not only the tools, such as CFD codes and wind tunnels, but also the personnel involved.

For illustrative purposes an aerodynamic design problem currently under investigation within the HICON project, the dropped hinge flap, is outlined below. The aim is to present the status of ongoing investigations in this area, it is by no means a solved problem and hence a lot of unanswered questions still exist.

3.1 Dropped Hinge Flap

Although the dropped hinge, or pivot, flap is not a new concept, it is being investigated within HICON as an alternative high-lift device. To date no Airbus passenger aircraft has applied the dropped hinge flap to its high-lift system[1].

The aerodynamic challenge in designing a high-lift system using a dropped hinge flap is the reduced freedom when designing appropriate take-off (e.g. low-drag) and landing (e.g. high maximum lift capability) settings. The single slotted Fowler flap with appropriate track kinematics, as has been applied on the majority of Airbus aircraft to date, allows the aerodynamicist to design take-off and landing settings relatively independently of each other. In simple terms, it is possible to design an optimum take-off setting without having to pay a penalty when designing the landing setting and vice-versa. An example of this is shown in Fig. 2.

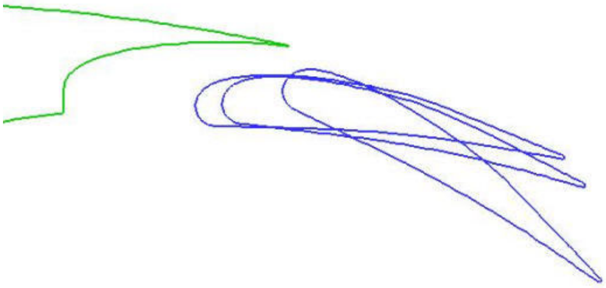

Fig. 2. Track kinematics.

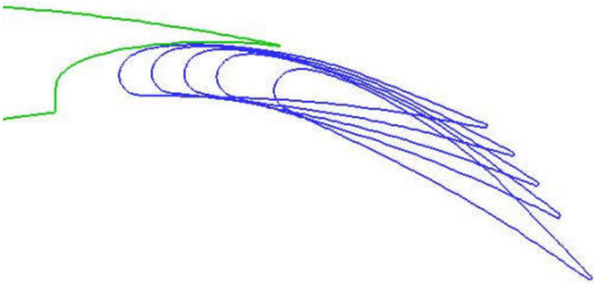

Fig. 3. Dropped hinge.

Due to the fact that the dropped hinge flap is deployed along a radius, the center being the hinge point located below the wing, the

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[1] The A400M has a fixed vane dropped hinge flap, is however not a passenger aircraft and has completely different design criteria

designer is only able to choose one target position (the flap position in the retracted position being the other target condition) in order to fully define the kinematics system. All other flap positions are a function of the flap angle and, for a given flap shape, cannot be adjusted or optimized without adjusting the original target position used to define the dropped hinge system in the beginning. This principle is highlighted in Fig. 3. If, as in this example, the dropped hinge flap is designed to have an appropriate position for the landing configuration (the flap position to the right in Fig. 3, which is the same as that for the track kinematics in Fig. 2), less than optimal intermediate, or take-off, configurations can result. If, on the other hand, an optimal take-off setting is chosen as the design criterion, this leads to a degraded performance in the landing configuration. The challenge lies in achieving the best compromise between both.

As a result, the dropped hinge flap brings certain aerodynamic constraints or limitations when compared to a Fowler flap with track kinematics. On the other hand, the dropped hinge flap promises to provide benefits in terms of weight and manufacture and maintenance costs. As well as this, in terms of the future challenges for high-lift systems being addressed within HICON, the dropped hinge flap may provide the designer with extra flexibility when designing for a steep approach capability. In this case the high-lift system needs to produce large amounts of drag without losing high-lift capability. This could be achieved by deploying a dropped hinge flap to angles beyond the point of flow separation on the flap (e.g. 50 degrees). This would also be possible with a single slotted Fowler flap with track kinematics, however the resulting device is likely to be considerably heavier.

3.2 2D CFD Analysis

2D analysis of representative high-lift wing sections remains one of the major design tools available to the high-lift aerodynamicist, even with the availability of industrialized 3D CFD tools. For this reason, significant effort is being made within HICON to establish a validated link between the predictive capabilities of 2D methods (in this case 2D CFD), 3D CFD and wind tunnel results (in both high and low Reynolds number conditions). Although 3D CFD methods have been available for some time, and have been successfully applied to a wide variety of design problems, the majority of these fall into the category of post-event investigations (e.g. the investigation of phenomena discovered following wind tunnel tests).

A typical example of a design exercise performed routinely with 2D CFD is a flap setting optimization (i.e. flap gap and overlap). An example of this can be seen in Fig. 4 for a dropped hinge flap. This analysis has been performed with a mid-board wing section in a landing configuration, the result being an optimal flap gap and overlap setting of 1.5% and 0% respectively, as indicated by the center of the red region (the percentage values refer to the gap and overlap[2] values normalized by the local wing chord). In this case the 2D section used in the calculation is parallel to the symmetry axis of the aircraft, not perpendicular to the wing leading edge. The local Reynolds number used in the calculation corresponds to the flight Reynolds number.

An increase in geometrical complexity without performing a full 3D analysis can be achieved by moving to 2.5D, or an infinitely swept wing. This is achieved relatively easily with CFD via the generation of a grid which is one cell wide, this cell having a sweep angle the same as the local sweep angle of the leading edge of the wing. The application of periodic boundary conditions to the sides of the grid allows the simulation of an infinitely swept wing. The results of this analysis for the same

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[2] The usual convention defines a positive overlap when the leading edge of the flap is ahead of the trailing edge of the wing, i.e. the wing “overlaps” the flap. In the figures shown in this paper the sign convention is the opposite, i.e. a negative overlap means the leading edge of the flap is ahead of the trailing edge of the wing.

setting variation displayed in Fig. 4 can be seen in Fig. 5. Of interest to the designer is the change in the optimal flap setting from 1.5%, 0% (gap, overlap) to 2.0%, 0%.

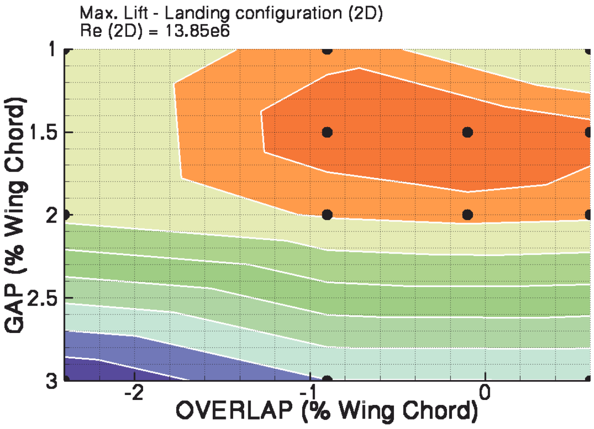

Fig. 4. Maximum lift coefficient, 2D CFD calculation, dropped hinge flap setting variation.

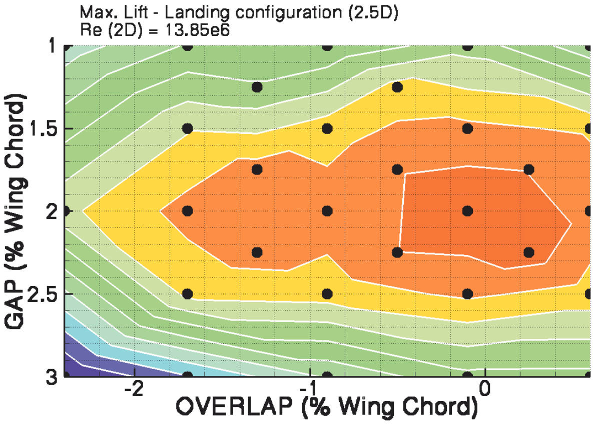

Fig. 5. Maximum lift coefficient, 2.5D CFD calculation, dropped hinge flap setting variation.

The influence of the Reynolds number on the computational results can be seen in Fig. 6, in this analysis the computations have been performed for the 2D configuration, and hence these results are to be compared to those shown in Fig. 4. In this case a local Reynolds number has been chosen which corresponds to a Reynolds number typical of that achievable in the Airbus low speed wind tunnels. And although there is an obvious change in the maximum lift achieved at the lower Reynolds number, the useful information is again the change of the optimal flap setting with the different Reynolds number. The higher the Reynolds number, the lower the value of the optimal gap setting. This has, of course, implications for the interpretation of wind tunnel testing results, depending on the Reynolds number used.

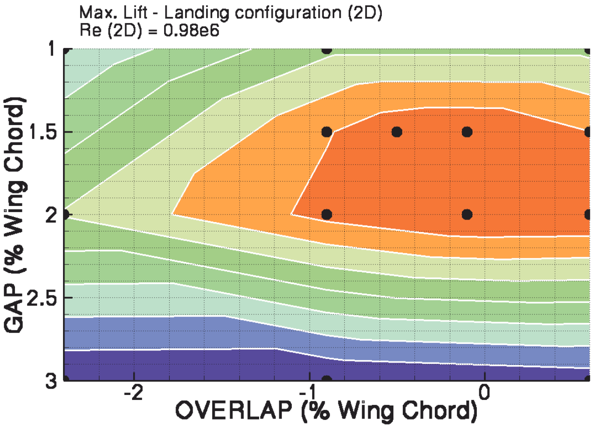

Fig. 6. Maximum lift coefficient, 2D CFD calculation, dropped hinge flap setting variation, Reynolds number effect.

3.3 3D CFD Analysis

The question of interest is how does a 3D CFD flap setting analysis compare to the results presented in the previous section? Prior to this exercise, no gap and overlap setting investigation had been performed with 3D CFD at Airbus.

Following a similar 2D setting analysis of the take-off configuration, a target setting for the dropped hinge flap was defined (as was outlined earlier, this was a compromise between optimum performance in the take-off and landing configurations). This setting lies in the center of the black box marked in Fig. 7. The corners of the box (A-D) represent the setting variations investigated with 3D CFD. Due to the time involved in generating the 3D data, a limited gap and overlap variation was performed, as is standard during wind tunnel testing.

The lift polars generated via 3D CFD are shown in Fig. 8. The Reynolds number used for the calculations is the same as that used in the

2D and 2.5D computations (i.e. flight Reynolds number). The 3D computations were performed using the standard grid generation and computation techniques as currently applied in the aerodynamics department and will not be discussed any further here.

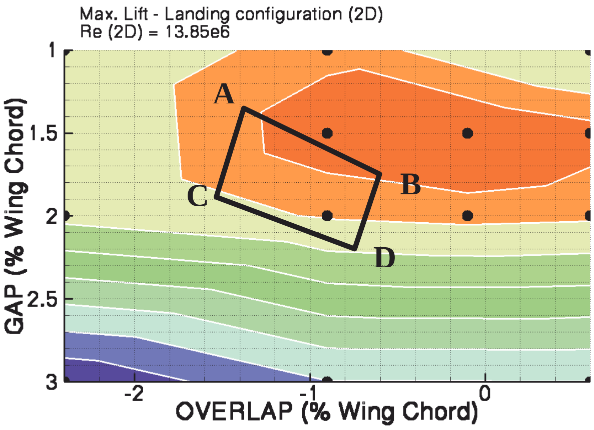

Fig. 7. 3D CFD setting variation, dropped hinge flap, based on the results of the 2D CFD setting variation from Fig. 4.

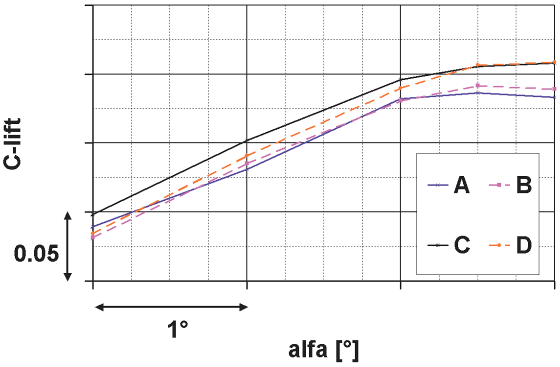

Fig. 8. Lift polars, 3D CFD setting variation.

In Fig. 7 it can be seen that the settings represented by points A and B produce a higher maximum lift than the settings C and D. This trend, however, is reversed in the results from the 3D calculations (Fig. 8). If, on the other hand, the 3D setting variation stencil is shown together with the results from the 2.5D CFD analysis (see Fig. 9), the comparison with the 3D CFD results improves considerably. In both cases setting A has the lowest maximum lift and setting C and D perform the best. It must be remembered, though, that the maximum lift capability of a 3D wing is highly influenced by local disturbances on the 3D wing (such as the pylon/nacelle region) and hence it is unrealistic to expect a perfect comparison between 2D (or 2.5D) analyses and 3D.

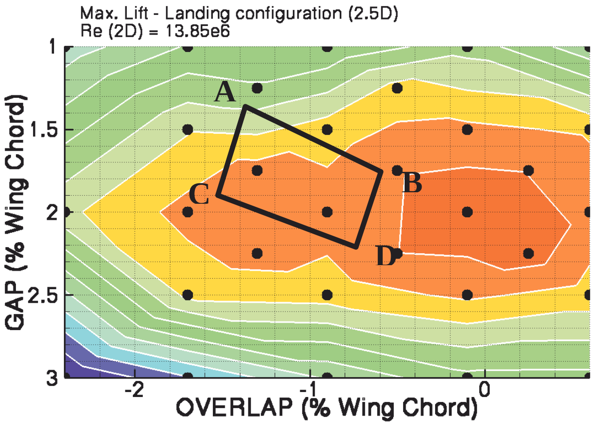

Fig. 9. 3D CFD setting variation, dropped hinge flap, based on the results of the 2.5D CFD setting variation from Fig. 5.

3.4 Wind tunnel testing

To date wind tunnel testing of the dropped hinge flap has been conducted in the Airbus LSWT Tunnel in Bremen. Although one of the aims of the project is to design and test new concepts under high Reynolds number conditions in the cryogenic wind tunnel ETW in Cologne, this is extremely expensive and can only be used to test selected configurations. As a result, a broader range of configurations have been tested at lower Reynolds number conditions (aeroacoustic measurements of configurations have also been performed, see Section 4), the aim being to generate a wider data base for validation purposes. It is planned to test two dropped hinge configurations during the upcoming HICON ETW test at flight Reynolds number.

The results from the gap and overlap variations of the dropped hinge flap performed at a Reynolds number of 1.4 million can be seen in Fig. 10. Although the configurations measured in the wind tunnel don’t exactly correspond to the setting variations performed via CFD (e.g. the difference between setting A and D in Fig. 7 and Fig. 9 is not a pure gap variation), the association between the wind tunnel and CFD setting variations shown in the legend in Fig. 10 is a reasonable approximation.

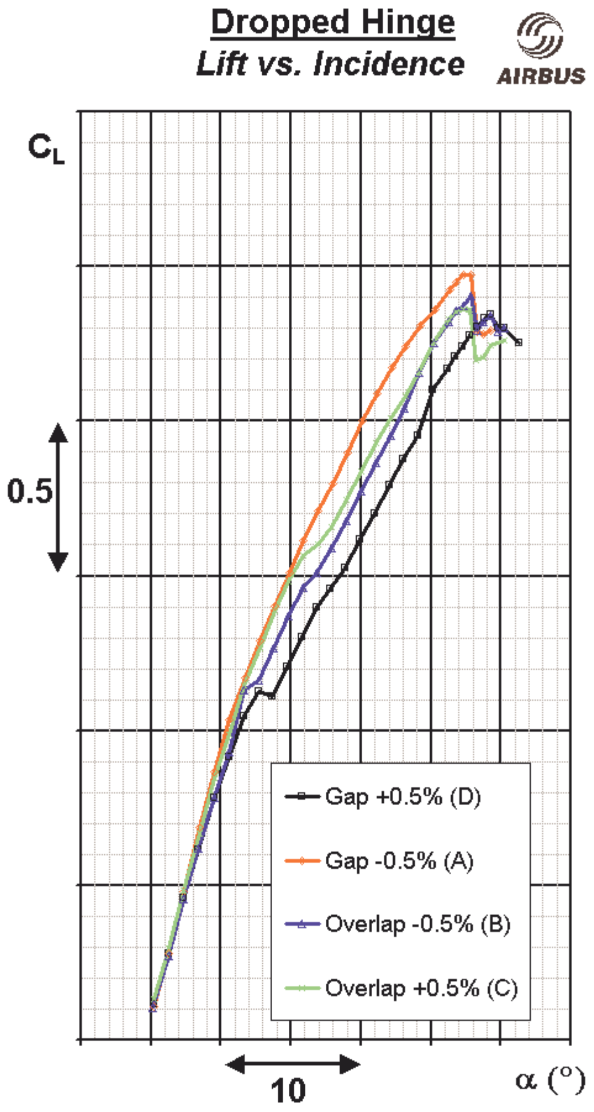

Fig. 10. Gap and overlap variations, wind tunnel results (LSWT Bremen), Reynolds number = 1.4e6.

The wind tunnel results show that the maximum lift is insensitive to the changes in overlap. This overlap insensitivity is a trend that has been seen in all CFD results to date. Changes in gap, however, have a large influence on the maximum lift, with the best aerodynamic performance obtained with the smallest gap value (setting A). This is in contrast to the 3D and 2.5D CFD results which predicted the worst performance for setting A.

The obvious question to arise is where does this fundamental difference between the CFD and wind tunnel results come from? The most obvious difference is the Reynolds number (CFD: 20e6, wind tunnel: 1.4e6), however results from the 2D CFD analysis suggest that a decrease in the Reynolds number used in the CFD simulations will cause an increase in the optimum gap value (the red region in Fig. 9 will shift downwards to higher gap values), changing nothing in the comparison as it currently stands. In the same manner, an increase in the wind tunnel Reynolds number would favor the setting with a smaller gap value, again causing no expected change in the current comparison (this needs to be confirmed).

3.5 Remaining work

Ongoing work within HICON concerning the dropped hinge flap is concentrating on the following topics:

- Influence of the Reynolds number on the 2.5D and 3D CFD predictions. What changes are associated with using the low wind tunnel Reynolds number (efforts to date have been focussed on the flight Reynolds number)?
- High Reynolds number testing. The HICON ETW test will deliver a limited experimental dataset concerning the experimental influence of the Reynolds number on the high-lift performance.
- 3D CFD. How well does 3D CFD capture the stall mechanisms which determine the value of maximum lift?

5 Conclusions

Ongoing efforts aimed at improving the aerodynamic high-lift design process are being conducted within the HICON project. These efforts are focused on the increased use of 3D CFD and high Reynolds number testing during the design process.

The status of the aerodynamic design of a dropped hinge flap has been presented. Dropped hinge flap setting variations have been performed with 2D, 2.5D and 3D CFD methods, the results of which have been compared to wind tunnel tests performed under low Reynolds number conditions. A good comparison between 2.5D and 3D CFD results (at flight Reynolds number) has been found for this study, however the trends identified with 2.5D and 3D CFD have not been seen in the low Reynolds number wind tunnel results. Future work within HICON will be investigating the reasons for these differences, the major focus being Reynolds number effects (both in the CFD and wind tunnel investigations) and the capability of 3D CFD to capture the high-lift stall mechanisms.

Acknowledgements

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References

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