The idea of increasing commercial aircraft’s efficiency is still an engineering challenge. Increasing efficiency can be achieved through reducing the aircraft’s weight, reducing the aircraft’s drag or other methods. Accounting for more of these objectives in the same aeroelastic optimization has proven to be a challenging effort. Recent development in aeroelasticity and the availability of more computational resources has made such preliminary design processes more accurate and meaningful.

**CURRENT TRENDS**

By 2020, aircraft should have become 50% more efficient. One way to partially achieve this is to increase the wing surface area that exhibits laminar flow. DLR (The German Aerospace Centre), under the LamAir project, developed a commercial aircraft concept designed with a forward-swept wing. There are several mechanisms that trigger the transition between laminar and turbulent flow and the sweep angle is one of them. The increase of the wing laminar flow area through designing a forward-swept wing can significantly reduce turbulence, and thus reduce drag and increase efficiency. The main drawback of forward-swept wings is the undesired twist-bending stiffness coupling leading to aeroelastic stability problems, such as wing divergence. Furthermore, the use of composite materials have made it possible to reach lighter and more flexible wing designs, potentially making divergence even more critical. The severity of this phenomenon made it clear that there is the need of a preliminary wing design and optimization process that accounts as well for the aeroelastic problem.

The optimization of the composite laminates can yield twist-bending coupling terms that could compensate for the wing divergence. Initially, such a tool has been developed at DLR while using the DLM (doublet lattice method) as an aerodynamic tool. Unfortunately, the default DLM cannot account for the wing airfoil thickness and wing twist, and it has an inaccurate compressibility approximation and cannot model the shock waves that commercial aircrafts usually encounter. These drawbacks of the DLM can be corrected by a CFD analysis and include the correction in the optimization process.
PREVIOUS WORK

The DLR’s previous research and development of the MDO process that can design a composite wing-box with aeroelastic constraints for a given set of loading cases, has already been published (Dillinger et al. 2012, 2013). The wing resembles an A320 wing, with a wing semispan of 17.89m, wing surface of 122.6m² and a sweep back leading edge of -16.8° and with several supercritical airfoils that have a relative thickness ranging from 11.5% up to 14%. The aeroelastic solver used here is NASTRAN, which can solve the FEM model, and also provides a DLM code. The two models are fundamentally different and they require a transfer of information in between. The DLM mesh is deformed with respect to the FEM deformations, while the forces yielded by the DLM are then introduced in the FEM structure. This fluid-structure coupling method is also known as splining. In this case, splining is done internally by NASTRAN.

THE FEM

The FEM model represents the wing-box as a shell model comprised of the wing-box skin, ribs, spars and stringers. The beam-like structures, such as stringers and spar caps, are modeled as beam elements. Each rib contains three spanwise points used for splining: on at the leading edge, one at the trailing edge and one in the center of the rib. They are connected by themselves through interpolation elements and they ensure a proper introduction in the structure of the wing twist moment induced by the DLM. The model also includes non-structural mass points such as fuel or other masses.

THE OPTIMIZER

The optimizer, ALDO, is developed and provided by TU Delft and it is a gradient-based optimizer that is highly oriented towards optimizing composites with respect to lamination parameters. The optimization objective is the wing-box skin mass reduction with both structural and aeroelastic constraints. The constraints are the wing-box skin panel strain failure and buckling failure, wing tip twist, the divergence pressure and the aileron effectiveness. The design variables are the thickness and the A and D matrices (membrane and bending stiffness) for each wing-box skin laminate. The optimization’s stopping criterion is the wing skin mass, which is checked after each iteration for any absolute difference smaller than 1%. The loading cases are chosen so that they are representative for a commercial aircraft, several cruising and rolling load cases, but also four loading cases chosen from the flight envelope. These last four loading cases are all symmetric trims: LC#1 has M=0.59 at h=0m with n=-1g, LC#2 is the same, but with n=+2.5g, LC#3 has M=0.87 at h=6,700m with n=+1g and LC#4 is the same as LC#3, but with n=+2.5g. All four are expected to drive the structural design and are mentioned here because the CFD solver for the aero- dynamics corrections will use these cases.

THE DLM

The DLM is one of the most basic and rudimentary tools one can use in steady and unsteady aerodynamic applications and its use can be extended up to compressible flow, as long as the free stream remains subsonic. The DLM equations yield a solution in the frequency domain, but for the steady case, where the frequency is zero, the DLM is reduced to the VLM (the vortex lattice method). This panel method is discretized through a plate-like mesh, hence it is unable to account for any wing thickness effects, wing twist or airfoil camber. As well, the equations use a Prandtl-Glauert compressibility correction, which exhibits an unrealistic singularity effect as the Mach number is reaching the value of 1. The unpredictability of wing shock waves, characteristic to transonic flow, is also not accounted for. All these inaccuracies made it important to find a correction method to the default DLM. Fortunately, later, NASTRAN developed a simple correction method that accounts for the wing twist and, to a certain extent, for the airfoil camber.

EULER CFD

The Euler equations are a simplified approach for aerodynamic calculations, where the viscosity and heat conduction terms are neglected. The Euler equations can approximate all the aforementioned effects that DLM cannot approximate, but there are also some known drawbacks. The Euler CFD does not predict any boundary layer, while the shock waves are approximated as stronger and closer to the trailing edge, when compared to the real phenomenon. The consequence is the introduction of a stronger negative wing twist moment in the structure. Here, the available CFD platform is TAU, a modern software system developed by the DLR that can predict viscous or inviscid flow about complex geometries. In this case, the splining of displacements and forces has to be done separately, outside both NASTRAN and TAU. This is achieved by using a MATLAB code designed especially for this purpose, of coupling NASTRAN with TAU.

VALIDATION AND COMPARISON

Before the implementation of any correction method in a costly and complex system, such as a MDO process, one needs to quantify the differences between DLM and CFD with respect to both wing geometry and flow parameters. A simple rectangular wing is constructed, where several geometrical parameters are varying, in order to separate the influence of each parameter on the results. The means of comparison are spanwise lift and twist moment distribution.

After a successful validation of the aeroelastic set-up, with DLM and CFD being in a very good agreement for simple and very thin wing geometries, one can notice that the DLM-CFD differences are mainly driven by the thickness effect. The CFD solver yields a 3-9% higher lift force, depending on the airfoil thickness, while the twist moment is still in good agreement. For cambered airfoils, the camber correction from NASTRAN has only a small in-
accuracy with respect to the lift, but the wing twist moment is underestimated by the DLM with up to 22%.

The next step is represented by the investigation with respect to the flow conditions. With the geometrical influences already known, one can now use the forward-swept wing geometry for four different increasing Mach numbers: incompressible \( M = 0.25 \), the critical Mach number \( M = 0.65 \) and two transonic cases \( M = 0.75, M = 0.87 \). The first case confirms the results of the previous investigation. The second shows a steady increase of the lift yielded by CFD, due to a more realistic compressibility approximation. The third case exhibits weak shocks, which induce a higher negative wing twist, while the fourth case shows strong shocks with a significantly negative wing twist. Figure 2 illustrates an example for \( M = 0.87 \).

THE CORRECTION METHOD
With the CFD-DLM differences known, one can proceed to implementing the aerodynamic correction inside the optimization. Basically, the correction is represented by the difference of the force vectors \( (X, Y, Z) \) between the DLM and CFD forces after splining them in the FEM model. These forces are then introduced in the optimization loop after which the process is restarted. The optimization without the CFD correction takes 29 iterations to reach convergence, but the solution is already close to being optimized after ten iterations. This information is used in the new configuration, where the structure is quasi-optimized for ten iterations using DLM, then the TAU module is started, the DLM-CFD force difference is computed and reintroduced into the structure, then the entire loop is restarted. In this case, a separate investigation showed that six loop repetitions are sufficient to achieve DLM-CFD force difference convergence. For the last series of structural optimization, the optimizer is not constraints to stop after ten iterations, but it follows its own wing-box mass convergence criteria.

THE RESULTS
The optimization with the Euler corrections finished after a total of three days. Figure 3 shows the mass development of the wing-box skin, with the starting design weighing 1,663kg. The vertical black lines show where the CFD solver is started. The optimized structure is 5.7% lighter than the uncorrected solution. The same figure shows the development of the divergence pressure per iteration. Unlike the uncorrected optimization, the divergence pressure is an active constraint (35,000Pa), meaning that the structure is used in a more efficient way. Wing tip twist and aileron effectiveness are not active constraints in this case.

Figure 1 and 2 show the comparison of the DLM-CFD \( \Delta C_p \) of the optimized solution for the four relevant load cases mentioned before. Figure 2 show the effect of the shock wave and its consequences in the wing-box twist moment. Basically, the higher negative wing twist moment of the corrected solution influences the stiffness in the trailing edge spar area, where more panels have their main stiffness oriented as such to compensate for twisting and buckling. Here, the stiffer trailing edge makes divergence an active constraint. Generally, the structural constraints and the failure modes follow the same trends as before, with the wing-box tip being driven by buckling failure, while the rest of the wing-box is mostly driven by strain failure. As a concluding remark, the Euler corrected optimization does not fundamentally change the results, but the additional wing twist has an influence on the wing skin stiffness orientations, which by themselves influence the wing’s aeroelastic behaviour.

References