INVESTIGATION OF CROSS-FLOW EFFECTS REGARDING LAMINAR FLOW CONTROL WITHIN CONCEPTUAL AIRCRAFT DESIGN

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Abstract: The objective, for instance of the "Flightpath 2050", to reduce CO2 emissions by 75 % until the year 2050 (with reference to 2000), poses strong requirements to manufacturers and operators to increase aircraft fuel efficiency. Besides improvements of operational and air traffic management the aim can be reached by increasing overall aircraft efficiency, i.e. mass reductions and improved aerodynamics. Regarding the aerodynamics, laminarization of aircraft surfaces is a promising technology to reduce friction drag, especially on the main wing of the aircraft. On swept wings of transport aircraft, transition from laminar to turbulent flow is mainly governed by three instability mechanisms: Tollmien-Schlichting instability (TSI), cross-flow instability (CFI) and attachment line transition (ALT). They can occur alone or in combination, which is strongly governed by Reynolds number and wing sweep angle. Due to the high Mach and Reynolds numbers of today's transport aircraft and thus high swept wings, cross-flow instabilities mainly have to be taken into account when talking about laminarization, since CFI will occur in the region of the leading edge. To suppress these cross-flow instabilities a suction system is needed. The size of this suction system, and therefore its mass and power offtakes, depends on the required strength of suction. This results in drawbacks regarding additional system mass and power offtakes on the engines. For this purpose, it is essential to evaluate a new technology such as hybrid laminar flow control on overall aircraft level.

To be able to capture three-dimensional effects as cross-flow and its instabilities regarding laminarization, highly sophisticated investigations are needed. While streamwise transition prediction with respect to TSI is often found in airfoil or low-swept wing design applications, a simultaneous reliable coverage of CFI for highly swept and tapered wing applications is rarely included within preliminary aircraft design, since these accurate computations, such as CFD, are not an option for the application within conceptual or preliminary aircraft design. This raises the questions in which way simple estimations and simplifications could be used, how several transformations differ from each other and where the limits are, i.e. how far they are from reality.

In order to answer these questions and derive an approach for conceptual aircraft design, in this paper first of all different transformation methods will be analyzed and validated for several applications. As simplification for infinite swept wings, often the so-called "simple sweep theory" (SST) is used, which is based on early swept wing investigations by Busemann[1] and provides transformation rules between 3D and 2D geometry and flow conditions. Since these simple 2D transformations neglect significant flow phenomena occurring on tapered wing geometries, for the more realistic case of a tapered wing also several approaches exist. Based on SST, some models use the shock position as an additional input, which is unfortunately itself influenced by 3D effects of the flow field. Another proposed method uses a conical 2.5D approach. It combines equations of sweep taper theory, i.e. an enhancement of simple sweep theory for tapered wing geometries, with conical flow assumptions. The latter are used for relating 2D and 3D pressure distributions, and are also the basis for formulation and solution of the compressible conical boundary layer equations.

For all these transformation methods 2D pressure distributions will be calculated with the flow solver MSES[2]. For this purpose an automated in-house method is used to transform freestream conditions as well as wing geometry, generate 2D flow solutions at discrete wing sections with MSES and translate the resulting 2D pressure distribution into a 3D pressure distribution. This will be done for different wings with increasing complexity, starting with an unswept rectangle wing, to a swept and a tapered wing, up to a kinked wing. The results will be compared and validated with a 3D-CFD solution using RANS.

In a second stage the different pressure distributions will be used as input for transition prediction. The results will be compared among each other and to CFD solutions for wing sections of a kinked 3D wing. Cross-flow will have an influence on pressure distribution of the wing and with this to the cross-flow instabilities as transition mechanism and therefore to the transition line. The impact of laminar area of the wing to its friction drag will be analyzed on overall aircraft level with the in-house conceptual aircraft design and optimization environment MICADO[3]. For a short range reference aircraft[4] the overall benefit can be evaluated in terms of block fuel, including the benefit of drag reduction as well as possible drawbacks of mass growth due to the additional system mass and snowball effects on the one hand and the influence on the engine performance due to power offtakes on the other hand.

As a further approach, it will be analyzed if suppression of CFI by increasing suction strength, resulting in increasing generator masses and power offtakes, will be more beneficial regarding fuel consumption than smaller generators and less aerodynamic efficiency. Finally, based on the results of the studies, a statement will be derived how accurate cross-flow has to be taken into account to evaluate hybrid laminar flow control in conceptual aircraft design.

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[1] Busemann, A.: Aerodynamischer Auftrieb bei Überschallgeschwindigkeit. In 5. Volta-Kongress, Rome, Italy, 1935.

[2] Drela, M.: A User's Guide to MSES 3.05. Massachusetts Institute of Technology (MIT), 2007.

[3] Risse, K., et al.: An Integrated Environment for Preliminary Aircraft Design and Optimization. In 8th AIAA Multidisciplinary Design Optimization Specialist Conference (MDO), Honolulu, HI, 2012. AIAA.

[4] Central Reference Aircraft data System (CeRAS): http://ceras.ilr.rwth-aachen.de