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Validation of the RANS-simulation of laminar separation bubbles on airfoils ☆

Validierung der RANS-Simulation laminarer Ablöseblasen auf Profilen

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Abstract

This paper presents RANS simulations of the low-Reynolds-number flow past an SD7003 airfoil at $Re = 6 \times 10^4$, where transition takes place across a laminar separation bubble. The transition prediction procedure using an approximate envelope method as well as a linear stability solver is discussed. The numerical results are validated against PIV- and force measurements obtained in several wind- and watertunnels and are also compared to XFOIL results. Good agreement is found within the operational range of the airfoil.

Zusammenfassung

In dieser Arbeit werden RANS Simulationen der Umströmung des Profils SD7003 bei einer niedrigen Reynoldszahl von $Re = 6 \times 10^4$ präsentiert, wobei die Transition über laminare Ablöseblasen stattfindet. Die Transitionsvorhersage mit einem approximativen Hüllkurvenverfahren sowie einem Verfahren zur Lösung der linearen Stabilitätstheorie wird diskutiert. Die numerischen Ergebnisse werden anhand von PIV- sowie Kraftmessungen aus verschiedenen Wind- und Wasserkanälen validiert und mit XFOIL Ergebnissen verglichen. Es ergibt sich innerhalb des Arbeitsbereiches des Profils eine gute Übereinstimmung.

Keywords: Laminar separation bubble; Transition; Numerical simulation

Schlüsselwörter: Laminare Ablöseblase; Transition; Numerische Simulation

1. Introduction

The aerodynamics of low-speed low-Reynolds-number flows over airfoils and wings has been studied for decades in experimental and numerical works. However, the research was often of an academic nature since there were few technical applications. One exception was the design of model airplanes for which a rich experimental data base grew over the years. Here the pioneering work of F. Schmitz [28] is mentioned, and much work was later performed by researchers at Stuttgart University, Germany [1,10]. More recently, M. Selig and co-workers developed advanced aerodynamic design methodologies for model airplane airfoils and performed a large amount of measurements [31,32]. The subject of low-Reynolds number flows does receive more attention presently as advances in the field of micro system technologies enable the development of Micro Aerial Vehicles (MAV) with a broad variety of applications. Dimensional analysis states that the Reynolds number is the governing parameter that determines lift and drag for a given geometrical shape and a fixed disturbance level of the incoming freestream flow. Recently developed MAVs with masses in the order of 100 g, i.e. the "Black Widow" [11], face Reynolds numbers from about $Re = 5 \times 10^4$–2×10^5. Important for this flight regime is that transition usually occurs in combination

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Nomenclature

c	chord length
c_d	drag coefficient
c_l	lift coefficient
c_p	pressure coefficient
f	frequency
H_{12}	shape parameter of the boundary layer
k	turbulent kinetic energy
Ma	Mach number
N	N-factor
Re	Reynolds number
s	length along curvature
Tu	turbulence level
u, v, w	velocity components
u', v'	fluctuation velocities
α	angle of attack
δ	boundary layer thickness
δ^*	displacement thickness
μ_t	turbulent eddy viscosity
ρ	density
ω	specific dissipation rate
θ	momentum loss thickness

Subscripts

crit	critical
ind	indifference point
tran	transition
e	boundary layer edge
∞	value at freestream

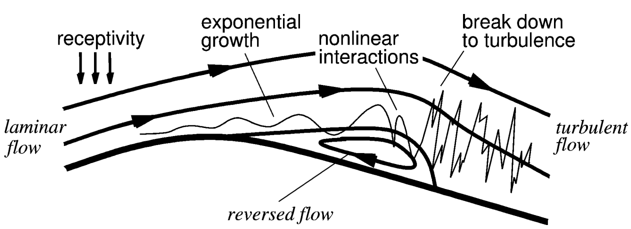

Fig. 1. Instability and transition in a laminar separation bubble, with a sketch of time-averaged streamlines.

with a large laminar separation bubble (LSB). The LSB is a flow where a laminar separation takes place that is in most cases caused by an adverse pressure gradient along the smooth aerodynamic surface. Small disturbances present in the laminar flow are strongly amplified in the shear layer of the separated flow and rapid transition to turbulence takes place. The turbulence, in turn, creates a large momentum transport normal to the shear layer so that the flow reattaches to the surface and a closed bubble is formed in the time-averaged mean. Laminar separation bubbles can have large, adverse aerodynamic effects. Usually, they create additional drag as they displace the outer inviscid flow. This results in reduced suction over the forward portion of airfoils and wings and decreases pressure recovery in rear parts, so the additional drag is mostly pressure drag. The increase of pressure drag depends on the size of the LSB, in particular on its thickness in the wall-normal direction. A more dramatic effect occurs if the transition process in the separated shear layer is relatively slow and the adverse pressure gradient is strong. Then turbulent momentum transport is not sufficient to close the bubble and a large separation occurs that extends right to the trailing edge. This causes a sudden loss of lift and a strong increase of drag along with significant hysteresis effects of force coefficients with varying angle of attack. Note that the break up of LSBs may be experienced over a broad range of Reynolds numbers.

The principal flow behaviour of a laminar separation bubble is sketched in Fig. 1. In the first stage of the transition process, external distortions, like freestream turbulence, acoustic waves or surface roughness, generate small, harmonic waves within the laminar boundary layer upstream of the separation. The behavior of the waves in the laminar boundary layer can be described by linear stability theory (LST) within a certain spatial region: unstable waves grow exponentially while traveling downstream. This linear process constitutes the second stage of transition. For the low-disturbance environment investigated in this paper, according to the research of Würz, Rist, Wagner, Lang and Marxen [17,19,38], the primary instability mechanism encountered in this stage is initially of the Tollmien–Schlichting (TS) type, and remains dominated by this type up into the separated flow region. There, a smooth shift over to the Kelvin–Helmholtz (KH) instability may take place, which can become dominant in the rear part of the second stage [5,26,27, 39]. This stage extends across a large portion of the flow compared to the third stage of transition, where the distortions become so large that saturation occurs and secondary instabilities can grow in the distorted boundary layer flow: This behavior is characterized with nonlinear interactions. Finally, the number of spatial and temporal modes grows rapidly and the ordered laminar structures break down into turbulence.

The investigation in this paper is focused on the flow around a SD7003 airfoil. It is chosen because it exhibits long and stable LSBs over a broad range of angles of attack for Reynolds numbers below $Re = 1 \times 10^5$.

2. Description of methods

2.1. Numerical methods

Aerodynamic design and analysis tools used for flows with laminar separation bubbles are presently restricted to 2D steady flows [6], and they are rather not reliable in their predictions of the break-up process of LSBs. For the future design of MAVs more general analysis tools are sought. Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES) of the flow during aerodynamic design cycles are not feasible because of the extreme demands on computational resources associated with this approach. This paper therefore presents the current