Numerical Investigation of Transonic Shock Oscillation on Stationary Aerofoils

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Abstract

The typical flight envelope of modern large-span aircraft, flying in the transonic flow regime, is characterized by the appearance of the following features: local supersonic regions closed by shock waves, strong interactions between shock wave and boundary layer, and flow separation. Boundary layer separation occurring in the transonic flow regime requires special attention and careful analysis because it can provoke the self-sustained oscillation of a shock wave (shock-buffet), even if a structure (wing) remains stationary. In general, shock-buffet is a large-scale flow-induced shock motion that involves alternating separation and reattachment of the boundary layer. Periodic shock oscillations on stationary aerofoils are experimentally well documented phenomena [4, 7, 8, 10]. They have also been detected using various viscous-inviscid interaction computational methods [3, 6], unsteady RANS-based methods [1, 9] and even the DES approach [2]. In spite of numerous experimental and computational studies in the last three decades, a reliable and efficient numerical simulation of shock-buffet remains an important problem in fluid dynamics.

This presentation shows a summary of an ongoing numerical investigation underway at the DLR Göttingen, dealing with the influence of various modelling parameters on numerical simulation of unsteady transonic flows. The focus of research lies on a simulation of self-sustained shock oscillation (shock-buffet) since this mechanism can play an important role in the aerodynamic and aeroelastic behaviour of modern large-span aircrafts. In the investigation the DLR-Tau code [5], a time-accurate RANS flow solver based on the finite-volume approach, is used. It employs an unstructured spatial flow field discretisation and dual-time stepping scheme for time-accurate (unsteady) calculations. Presented is an analysis of the results obtained with URANS simulation and Spalart-Allmaras-based Detached-Eddy Simulation (DES) of shock-buffet phenomena occurring on three different profiles: two conventional symmetrical NACA aerofoils (64A010 and 0012) and a supercritical NLR 7301 aerofoil.

The first part of presentation deals with the 2-D URANS results. The main objectives of these simulations are: (i) to analyse the role of the profile geometry (profile shape, maximum profile thickness), (ii) to investigate the influence of modelling parameters (turbulence modelling, flow solver spatial discretization schemes, temporal resolution) and (iii) to gain insight into the underlying physics (analysis of shock-buffet excitation mechanism). Two linear eddy-viscosity-based turbulence models are used: the 1-equation model of Spalart and Allmaras (S-A) and the linearised explicit algebraic (LEA) 2-equation k-ω model. For the spatial gradients of fluxes, both upwind and central differencing schemes have been tested. It is shown that the appropriate choice of modelling parameters for shock-buffet URANS simulations depends on the aerofoil geometry. The 2-equation turbulence model is more successful than the 1-equation model in predicting the shock-buffet phenomena on thin symmetrical aerofoils. For a thick supercritical aerofoil, on the other hand, the 1-equation model gives the buffet onset boundary closer to the experimental
data. With respect to the spatial discretisation scheme, the central solver returns more accurate results for flows with weaker boundary layer separation occurring on thin aerofoils. The upwind solver scheme, while overpredicting the separation effect, is more accurate in capturing the shock wave location and this could be an explanation for a better buffet prediction on a thick NLR 7301 aerofoil. Regarding the analysis of physical mechanism of buffet phenomena, it is shown that relatively high incidence angles ($\alpha > 4$ deg) are necessary to provoke the onset of shock-buffet on a thin aerofoil (maximum thickness about 10% chord). With increasing thickness the buffet onset shifts towards lower $\alpha$-values and, in the case of the thick supercritical aerofoil, buffet can occur even at small negative incidence angles. It is also shown that buffet reduced frequency is independent of the aerofoil thickness, i.e., for all three profiles the reduced frequency values are in the range $0.4 < \omega^* < 1.0$. Since three geometrically different aerofoils have the same chord length dimension ($c=1$), similarity of calculated reduced frequencies hints at the possible acoustic origin of buffet excitation mechanism [2, 7]. In such a mechanism the crucial role is played by pressure waves propagating through the flow field and spreading the disturbances in both upstream and downstream directions.

For those shock-buffet cases where massive boundary layer separation and detachment of eddies are present, the RANS approach shows its limitations which are well described in literature. The DES method, which works as a RANS model in the attached boundary layer region and as a Sub-Grid-Scale model in separated regions (LES simulation), can bring a significant improvement for the simulation of such flows. One selected buffet test case for a NLR 7301 aerofoil is calculated with the DES technique based on the one-transport-equation model of Spalart and Allmaras. The motivation behind the DES simulation is twofold. Firstly, a method less dependent on the choice of the particular turbulence model is tested and compared to the URANS. Secondly, the applicability of DES to transonic flows with strong unsteady shock/boundary-layer interaction is investigated. Until presently the DES has been applied mostly to flows with massive separation induced by geometry, i.e., stalled aerofoils at high angles of attack. However, in this study the fundamental processes occur in the near-wall region with flow separation being shock-induced and the separation point moving with the shock. The recirculation bubble remains attached to the surface while travelling downstream, until it finally separates from the surface after reaching the trailing edge. This results in a variety of issues which have to be further investigated (avoiding grid induced boundary layer separation while ensuring an adequate grid resolution in regions of detached eddies).

References


