Numerical Simulation of the Flow Field Around the Stratospheric Observatory for Infrared Astronomy

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Summary

Results of steady and unsteady RANS computations of the flow around the Stratospheric Observatory for Infrared Astronomy SOFIA are presented. The observatory consists of a Boeing 747 SP with an open port in the fuselage to house a 2.5 m infrared telescope for astronomical remote sensing purposes. Results of CFD-simulations, carried out at the University of Stuttgart, show that URANS is able to capture the main effects of the unsteady cavity flow and acoustics inside the SOFIA telescope port. Pressure spectra taken at several points on the telescope's surface point out the presence of unsteady pressure fluctuations at discrete frequencies. Results compare well with experimental data, generated by NASA in wind tunnel investigations with a 7% model of the SOFIA aircraft.

1 Introduction

NASA and DLR are working together within the SOFIA project to study the universe in the infrared spectrum. Astronomic objects that emit most of their radiation at these wavelengths are almost invisible from earth as the atmosphere absorbs the main part of the IR-radiation. Therefore the SOFIA aircraft carries an infrared telescope above the troposphere, where atmospheric perturbations are negligible. The telescope is located inside a cavity in the rear part of the fuselage (see Figure 1). During observation it will be exposed to the free atmosphere. The success of the whole project depends mainly on the performance of the telescope and its image stability. Vibrations of the telescope's structure deteriorate the pointing accuracy and are to be reduced as much as possible. Active and passive control systems compensate vibrations that are initiated by the aircraft structure and the unsteady flow. A main disturbance source on the telescope are the unsteady pressure loads evolving from the flow over and inside the telescope port. NASA successfully designed and optimized a passive shear layer control device that keeps the shear layer stable and reduces the fluctuations inside the cavity [9]. A convex shaped aperture at the downstream edge of the opening accelerates the boundary layer downstream and prevents the shear layer from uncontrolled oscillation. Long-term improvement of the telescope's performance is one of the main objectives, it requires a profound understanding of the prevailing flow phenomenons like fluid dynamics and acoustics.
1.1 Characteristics of Unsteady Cavity Flow and Acoustics

The flow over open ports and cavities in general is characterised by self sustained pressure fluctuations [10]. The shear layer spanning the opening of the cavity amplifies flow disturbances travelling downstream, that are scattered into acoustic waves at the downstream corner (see Figure 2). These acoustic waves propagate upstream inside and outside the cavity and excite further disturbances in the shear layer, creating a feedback loop. Frequencies with a phase lag of a multiple of $2\pi$ are being amplified, yielding a selection of discrete modes. Rossiter [10] found that the frequencies can be represented by the semi empirical equation

$$f = \frac{U}{L} \frac{|m - \gamma|}{|1/K + M|}, \quad (1)$$

where $f$ is the frequency of the mode $m$, $L$ is the reference length, $M$ the Mach number and $\gamma$ and $K$ are empirical constants. $\gamma$ represents the phase delay of disturbances that are scattered at the downstream corner, $K$ is the average convection speed of disturbances in the shear layer. The existence and the magnitude of these Rossiter modes depends basically on the stability characteristics of the shear layer that evolves from the boundary layer in front of the cavity [11]. The relevant boundary-layer parameter is the momentum thickness $\delta$. Small values in general lead to higher shear-layer disturbance amplification and hence to higher fluctuation levels inside the cavity. Rossiter modes transport energy from the external flow into the cavity. If acoustic resonance frequencies of the cavity are close to these Rossiter frequencies, fluctuation levels are further increased as Rossiter modes trigger acoustic standing waves and lock in at their resonant frequencies [3], [6].

1.2 Flow Solver

Unsteady RANS computations are performed with the Finite-Volume RANS-solver TAU that was developed by the Institute of Aerodynamics and Flow Technology of DLR [5]. The code solves the unsteady, compressible, three-dimensional Reynolds-averaged Navier-Stokes equations on unstructured or hybrid grids. Different cell types can be applied to account for different flow situations. Structured prismatic cells allow for high resolution in boundary layers with strong gradients in wall normal direction, tetrahedral elements facilitate the automation of the meshing procedure for complex geometries.