AXISYMMTERIC INVESTIGATION OF THE VAC S6 SHORT NOZZLE WITH FORCED EXTERNAL FLUCTUATION
ATAC – TEST CASE 1B

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1. Introduction

The present study examines the nature of separation shocks in over-expanded axisymmetric nozzles at a defined pressure ratio under steady viscous flow conditions. Furthermore unsteady computations on hybrid meshes are carried out for simulations of a realistic nozzle configuration. Data of existing experiments by [1] in the FFA HYP500 wind tunnel, are used in both cases to underline the achieved numerical results. The unsteady simulations show that the viscous shock system in the nozzle can be treated as a damped oscillator as already pointed out by R. Schwane [2].

2. Numerical tools

The presented investigation is carried out by using the hybrid structured/unstructured DLR-Navier-Stokes solver TAU, which is validated for a wide range of steady and unsteady sub- trans- and hypersonic flow cases [3].
TAU is a second order finite-volume flow solver for the Euler and Navier-Stokes equations in integral form. Different numerical schemes like cell-centred for sub- and transonic flow and AUSMDV for super- and hypersonic flow conditions are implemented. Second-order accuracy for upwind schemes is obtained by the MUSCL extrapolation in order to allow the capturing of strong shocks and contact discontinuities. A three-stage Runge-Kutta scheme and an implicit LUSGS scheme as additional option is implemented to advance the solutions in time for steady flow fields. For acceleration of the convergence local time stepping, implicit residual smoothing and full multigrid are available.
For time efficient and accurate transient flow simulations a dual time stepping scheme, following Jameson is implemented, which is an implicit algorithm not related to the choice of the smallest timestep in the flow field. The time derivative in the Navier-Stokes equations is discretized by a second order backward difference, resulting in a non-linear equation system which converges towards the subsequent timestep by using an inner pseudo-time. With this approach the performance of time accurate computations can be accelerated by 2-3 orders of magnitude. Several one- and two equation turbulence models are available for steady simulations. In the presented RANS-cases the one-equation Spalart-Allmaras (SA) model is used. During the last years modern turbulence models like Detached Eddy Simulation (DES) are implemented [4] but not used in the present study.

3. Grid generation

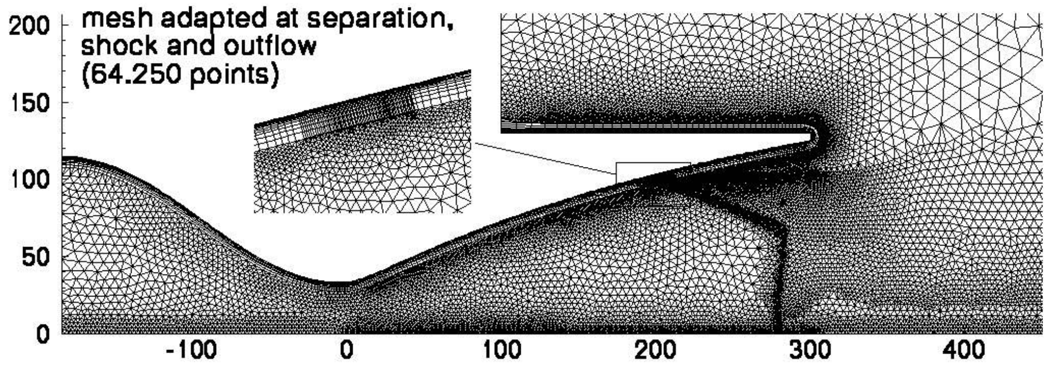

Fig. 1 Hybrid VAC S6 computational grid after adaptation.

For the nozzle calculations hybrid unstructured meshes including tetrahedral and prismatic cells are generated. Concerning the internal flow, unstructured cells allow a faster mesh generation and a better adaptation. Nevertheless the resolution of the viscous flow in the boundary layer requires structured cells in this area. The mesh density is adapted locally corresponding to the current separation and shock position (Fig. 1). For the boundary layer a first cell spacing corresponding to a y^+ of 0.5 along the nozzle length is applied.

4. Steady results

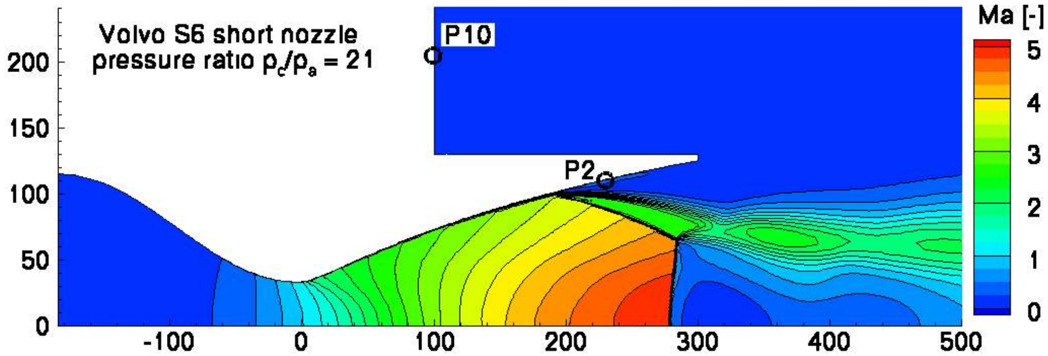

Fig. 2 Mach number distribution of the Volvo S6 short nozzle

The main issue of the steady computations is the validation of the numerical results by comparison with experiments of Torngren [1] in the modified FFA HYP500 wind tunnel facility at FOI. These experiments, sponsored by ESA/ESTEC, were carried out with a Truncated Ideal Contour (TIC) sub scale nozzle called Volvo S6 short nozzle. For the database pre-heated air at a temperature of T_c=400K and a stagnation pressure up to p_c=25 bar was expanded in the nozzle. A Special valve consisting of a static and a rotating slotted disk allows frequencies of the external pressure between 0 and 900Hz. Steady as well as unsteady experiments could be performed. The steady simulations show the dependency of separation and shock position on the ratio between chamber and ambient pressure (P_c/P_a). The Mach number distribution in Fig. 2 contains the well resolved Mach disk for the overexpanded Volvo S6 nozzle. Fig. 3 illustrates the wall pressure distribution for pressure ratios between 14.5 and 43.4. It demonstrates the downstream motion of the separation position with increasing pressure ratio. As visible the numerical calculations are completely confirmed by the experimental results.

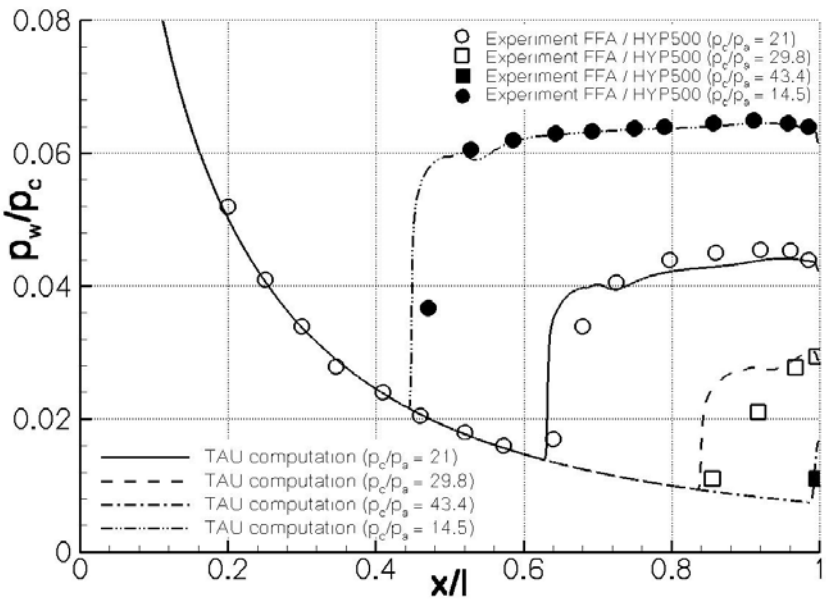

Fig. 3 Steady wall pressure at different pressure ratios. Reference length l=300 mm. Experimental data from [1]

5. Time-accurate results

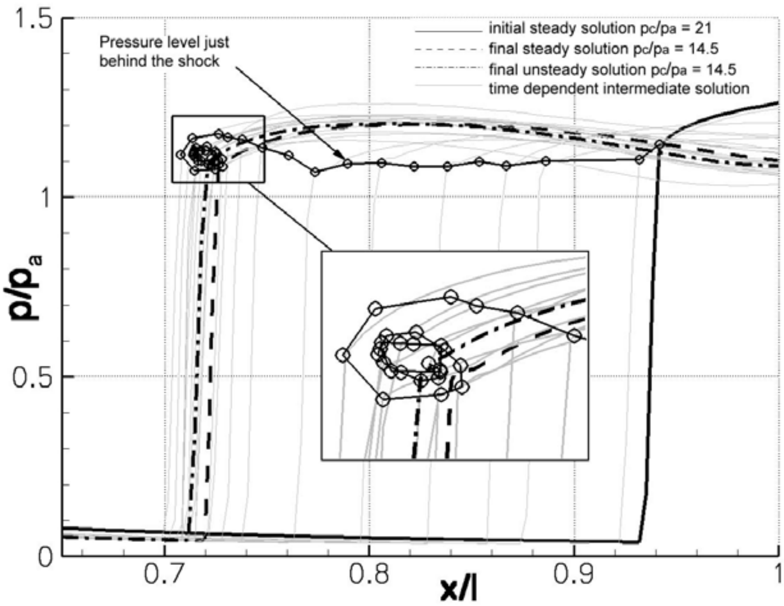

Fig. 4 Unsteady shock position after sudden decrease of pressure ratio p_c/p_a from 21 to 14.5

In former investigations by R. Schwane [2] the unsteady shock system in the nozzle has shown essentially the behaviour of a damped oscillator. Numerical examinations of these characteristics are performed by a sudden decrease of the chamber pressure. By this technique the shock is forced to move upstream and settle at a new fixed position according to the given pressure ratio. However, if the expected behaviour is appropriate, the shock should overshoot this position, performing a damped oscillation. This behaviour is indeed displayed in Fig. 4 where the pressure distribution on the centreline of the nozzle is plotted. Every vertical pressure peak describes the shock position at a different time. This is just the behaviour of a sudden excited damped oscillator.

In the experimental investigations further unsteady test runs are included [1], i.e. variations of the ambient pressure with respect to harmonic pressure fluctuations. Several unsteady pressure transducers, located inside and outside of the nozzle, realized time dependent pressure fluctuations. Fig. 5 shows the measured pressure at the transducer P2 corresponding to x/l = 0.767 in comparison with the external pressure, measured by the transducer P10 (see Fig. 2). As P2 is fixed for the wind tunnel set-up, several pressure ratios are generated in the experiments to investigate different flow conditions at the same position.

For a ratio P_c/P_a=20.2, P2 is located inside the separation at all times. Neither a significant phase shift nor a change in the amplitude is visible. at P_c/P_a=24.4 the separation moves forward and backward across the transducer. The resulting signal shows a higher amplitude with an approximated phase shift of 30° w.r.t. the outer pressure. For attached flow at P2, nearly no pressure signal can be measured. This behaviour agrees well with the simulations at a frequency of 40 Hz. In this case, between x/l=0.804 and 0.577, instead of the pressure ratio the positions for the sampling of the wall pressure are varied. The behaviour is the same as in the experiments. To simulate the wind tunnel test case with a frequency of 150 Hz it is for numerical reasons necessary to vary the inflow conditions instead of the ambient pressure. As the separation and shock position is mostly dependent on the pressure ratio between ambient and chamber pressure the results are similar to the experiments with the exception of x/l=0.534. At this position inside of the separation the pressure is influenced by the inflow conditions and consequently an oscillation is visible in contrast to the experimental case with ambient pressure variation. As a conclusion the characteristics of the shock similar to a linear oscillator could be shown by different techniques.

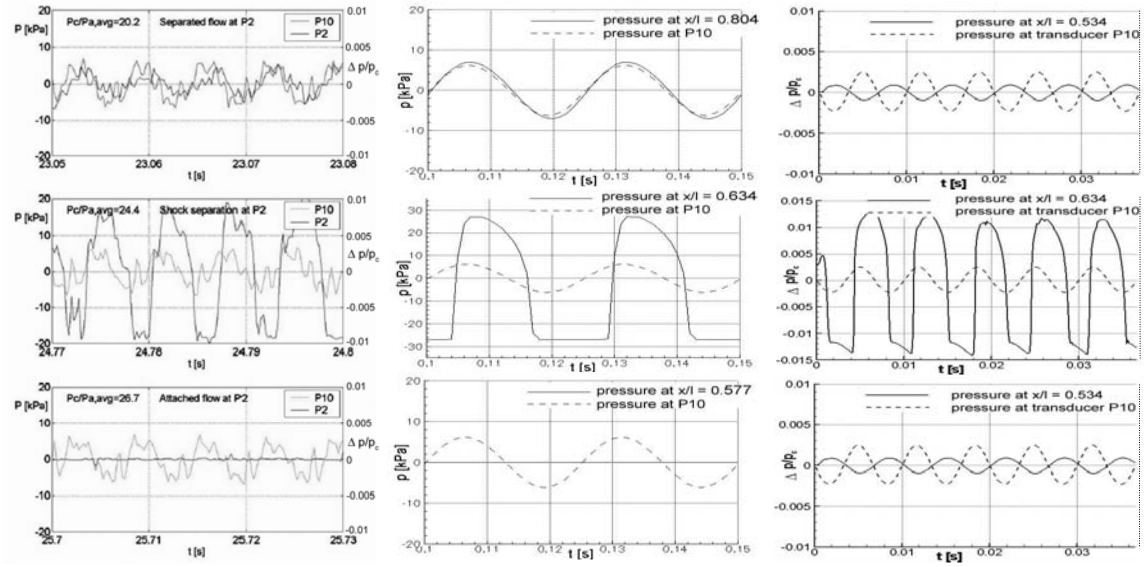

Fig. 5 Time dependent pressures at transducer P2 (x/l = 0.767) and P10 (ambient) at different frequencies. Left: Torngren [1], middle: CFD 40 Hz, right: CFD 150 Hz.

6. Conclusion

In the present study an over-expanded VAC S6 short nozzle was investigated and simulations of an unsteady buffeting coupling were carried out. The results show a good comparability with experimental data and emphasize the applicability of the chosen technique for transient nozzle flow in the investigated frequency regime.

References

[1] L. Torngren: Correlation between Outer Flow and Internal Nozzle Pressure Fluctuations. Proceedings of the 4th European Symposium on Aerothermodynamics for Space Vehicles, Capua, Italy 15-18 October, 2001, (2001)

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