PIV MEASUREMENTS IN SUB- AND SUPERSONIC FLOW
OVER THE DELTA WING CONFIGURATION ELAC
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Abstract

The roll-up of the vortex sheets of primary and secondary vortex over the leeward side of the delta wing configuration ELAC was examined using oil flow pattern, vapour screen and particle image velocimetry. Detailed information are gained concerning flow separation and reattachment by combining these methods.

1 Introduction

The governing factor of the lift force of delta-shaped wings is the vortex system over the leeward side when flow separates at positive angles of attack. For this reason a knowledge about separation and roll-up of the flow is of fundamental importance. In the present study for the flow field measurements at a Mach number 2 over a model of the delta wing ELAC was investigated. First a flow visualization with oil film technique and vapour screen was applied to gain information about the supposed vortex system. Then twodimensional PIV measurements in planparallel and orthogonal sheets over the leeward side of the model were realized.

The oil flow technique is suited to visualize the flow pattern of an air flow close to a surface. The observed pattern of the flow shows the position of flow separation and reattachment [1], so that information about the flow in the outer region can be gained.

A quantitative statement concerning the vortex positions in the outer flow region can be obtained by applying the vapour screen technique in supersonic flows. This is a light sheet technique using the condensed moisture of an air flow as tracer particles. Due to the size of particles the initial uniform concentration of the fog is changed by centrifugal forces in the vortices of a flow field. McGregor examined the required flow conditions for several Mach numbers and humidities [2].

The velocity distribution of the flow field was investigated using particle image velocimetry (PIV) at sub- and supersonic speeds. While the application of PIV at low speeds is already well known only a few measurements have been taken at supersonic flows. Humphreys [3] realized measurements at a Mach number of 6 with PIV. Due to the velocity lag of particles versus fluid flow the results represent the limit of velocity measurements when investigating the particle velocity of the added tracers. Raffel et al. [4] successfully measured the velocity distribution at a trailing edge of a cascade blade at Mach 1.27 and 1.4. Expansion waves and shocks were detected. The corresponding vorticity distribution showed two shear layers downstream of the trailing edge.

With the help of this twodimensional PIV technique and the combination of multiple measurements at different light-sheet positions the velocity distribution in all dimensions was obtained. At subsonic speed measurements were only taken at planparallel light sheet positions and the third absent component was reconstructed by applying continuity equation. Hereby a
comparison of compressible and incompressible flow can be provided.

2 Test facilities and Model of ELAC

The experiments in supersonic flow were carried out in a suction type trisonic wind tunnel. During a run the air is sucked through the naval nozzle, the test section (0.4x0.4 m²) and finally the diffusor in vacuum tanks with a volume of 380 m³. Dependent on the Mach number, which may vary from 0.2 to 4, the testing time is 3 s to 10 s. The test conditions were 10° angle of attack at a Mach number 2. According to the Mach number the Reynolds number was 3.6x10⁶.

The PIV measurements in subsonic flow were performed in a low speed wind tunnel driven in Eiffel configuration. The mean flow \( u_\infty \) was 11 m/s at angles of attack of 10° and 20°. The equivalent Reynolds number was 2x10⁵.

Subject of investigation was the flow around the delta wing configuration ELAC. This hypersonic vehicle is a two-stage-to-orbit transport system. It was developed in the Collaborative Research Center „Grundlagen des Entwurfs von Raumflugzeugen“ (SFB 253) of the German Research Association DFG. Figure 1a shows a sketch of this configuration with second stage, which is designed for stage separation in an altitude of 30 km. Further details can be found in Engler et al. [5]. It is a delta shaped lifting body with round leading edges and different semi-elliptic cross-sections. The leading edge angle is 75°. A 1:240th scaled model of the first stage of ELAC was used for the experiments, see figure 1b.

3 Flow Visualization with Vapour Screen and Oil Flow Pattern

3.1 Vapour Screen.
Flow visualization with vapour screen can be applied to supersonic flows. While usually experiments were carried out with dried air for supersonic testing, the vapour screen methods need moist air.

During expansion in the laval nozzle a uniform fog in the test section is formed by condensation of the moisture because of dropping temperature and pressure. Due to the velocity lag of big particles versus fluid flow in the area of vorticities, the dropled concentration declines to vortex centers. The change of concentration can be visualized by illuminating a plane within the flow with the help of a light sheet optic and a continuous wave laser. The resulting vapour screen is then recorded with a camera situated outside the test section. Correction of the distorted picture from the light sheet is established by determing the distortion of a calibration picture.

Attention has to be spent towards the Mach number because the latent heat of the

Figure 1a,b: a) Two-Stage-To-Orbit hypersonic transport system ELAC with second stage and propulsion system. b) Wind tunnel model for the experiments of the first stage of ELAC.
condensation process is added to the flow. McGregor gives an approximate relation for the correction of the Mach number [2]. The examination of the amount of moisture in the flow concerning best contrast of the taken pictures resulted in a relative humidity of 23% at ambient pressure and a total temperature of $T_t = 298$ K for this wind tunnel.

3.2 Surface Flow pattern.
The oil film technique is a standard technique for wind tunnel experiments. A mixture of oil and powder is applied to the surface of the model. A pattern of the flow close to the surface is then generated by viscous stresses acting on the oil-air surface.

For intermittently working wind tunnels it is advisable to use a volatile oil so that at the end of testing time just the streaky deposit of the powder remains on the model surface. A mixture of lamp oil and a fluorescent dye was used for experiments at the ELAC configuration. Care has to be taken by coating the model because a too thick paint changes the boundary condition for the air flow.

With this technique the positions of flow separation and reattachment can be shown. A more detailed analysis of the oil film technique can be found in Squire [6].

3.3 Results.
Figure 2 shows the combination of a vapour screen and an oil flow pattern of the leeward side of the hypersonic configuration ELAC 1 at a Mach number 2 at $10^\circ$ angle of attack. The vapour screen has been corrected to a front view and the oil flow pattern is shown as a top view on the model surface.

Due to the rounded leading edges of ELAC flow separates with a squeeze-off separation at angles of attack larger than $6^\circ$. At $10^\circ$ angle of attack flow separates at a relative spanwidth $z/b = 98\%$. It enrolls into the primary vortex sheet and reattaches at $z/b = 38\%$. The area of primary vortex is indicated by the dark area of the vapour screen in figure 2. The oil flow pattern also indicates a secondary separation, which cannot be seen in the vapour screen. The reason herefor being the secondary separation having one order of magnitude less vorticity than the primary separation. Consequently the condensated water droplets were not deflected by centrifugal forces as they were in the primary vortex.

Furthermore the sense of rotation of the vortices is indicated by the oil flow pattern. Primary vortex is rotating counter-clockwise and secondary vortex clockwise.
Figure 3 depicts the corresponding vortex topology according to the investigation of Peake and Tobak [7]. Primary and secondary separation are labeled $S_1'$ and $S_3'$, the corresponding positions of reattachment are $S_4'$ and $S_2'$.

4. Velocity Measurements using Particle Image Velocimetry

The velocity distribution over the leeward side of the model of ELAC was achieved using particle image velocimetry (PIV). The influence of compressibility was also investigated by taking measurements in a low speed wind tunnel.

Classical PIV is suited to measure in a two dimensional observation area the in-plane velocity components. This is attained by illuminating a particle laden flow with a pulsed light sheet. Then a photograph of this light sheet is taken. The so produced recordings are evaluated with autocorrelation using a semi-optical system as e.g. described in Molezzi and Dutton [8].

Especially for the application of PIV to supersonic flow the flow tracking capabilities of the tracer particles are of fundamental importance. For this reason the velocity lag of tracers versus fluid flow was investigated in an experiment over a flat plate with sharp leading edge. The transport in vortical flow fields was examined theoretically by a solution of the Basset-Boussinesq-Oseen (BBO) equation. Attention has to be paid towards size, density and refractive index of particles, because the amount of scattered light by the tracers requires big particles while the tracking capabilities demand small ones with a low density for air flows.

4.1 Apparatus

Due to vibration caused by the wind tunnel during the run and limited optical access, a complex experimental set-up had to be applied. The light-sheet was generated with help of a double cavity Nd:YAG laser and appropriate optics. The output energy of the laser was 170 mJ per pulse at a wavelength $\lambda$ of 532 nm.

First a telescopic optic was used to generate an approximate parallel beam. With a second telescopic optic the focus was adjusted to the test section of the wind tunnel to get a small light sheet. The height of 50 mm was achieved by using a concave cylindrical lens. The light sheet was cast through the housing of the wind tunnel and through the laval nozzle into the test section as shown in figure 4.

The camera was situated outside the test section. Due to vibrations the whole optical set-up including camera, light-sheet optics and laser was mounted on shock-absorbers.

![Figure 4: Experimental set-up for the application of PIV to the AIA trisonic wind tunnel with a double-cavity Nd:YAG laser, camera and appropriate light-sheet optics.](image)

Figure 5: PDA measurement of the size distribution of the used oil aerosol.
Appropriate tracer particles were produced with the help of an air operated aerosol generator. According to a contribution of Echols and Young [9], 36 Laskin nozzles generated an olive oil aerosol with the size distribution shown in figure 5. The averaged size of the oil droplets was 1.95 µm.

A similar but less complex set-up with a pulsed ruby laser was used for the PIV measurements in the low speed wind tunnel, see Lang and Limberg for details [10].

4.2 Particle slip in supersonic flow.
The particle slip of the used oil tracer particles was investigated by measuring the velocity distribution over a flat plate with sharp leading edge at a Mach number $Ma = 2.02$ and $\alpha = 6.3^\circ$. Figure 6b shows the change of the normal velocity component as a function of the distance normal to the oblique shock of the flow.

Figure 6b shows also the theoretical expected behaviour of the particles obtained by a solution of the BBO equation, see e.g. [11]. Just the supposed drag coefficient $c_D$ by Melling [11] gives a too large estimate of the normal velocity component, because his formulation for the drag coefficient is only applicable to a particle Reynolds number $Re_p$ less than 1. Actually $Re_p$ is 3.5 at the front of the oblique shock, so that the extended formulations of Oseen, Goldstein and Abraham give better results [12,13].

It is shown that the used particles require a distance of approximately 10 mm after the shock to decelerate to the ambient fluid flow velocity. The corresponding relaxation length is 1.5 mm. A statement concerning accuracy of the measurements is gained by analysis of the tangential velocity component in figure 6c. A maximum relative deviation of 2.5% is achieved.
The transport of the particles in vortical flows was estimated using the investigation of Raju and Meiburg [14]. A solid body rotation is supposed to give the velocity distribution of the flow field. For the vorticity of the solid body vortex a value of $\Omega_0 = 3 \times 10^4$ 1/s was supposed according to the results of a numerical simulation of the flow around this configuration at same test.

Figure 7 a,b: Results of PIV measurements at $u_\infty = 11$ m/s. a) Velocity and vorticity distribution in a crossflow section at $x/l = 62$ % and 10° angle of attack. b) Vorticity distribution in four cross sections at 20° angle of attack.

Figure 8 a,b : a) Velocity distribution in cross sections and streamlines over the leeward side of ELAC at $u_\infty = 11$ m/s and 20° angle of attack. b) Non-conical velocity components show primary and secondary separation at $x/l = 62.7$%.
conditions [15]. The particle velocity at time $t = 0$ was set to $v_0$ of the fluid flow at the certain radius $r = 0.02$ m. Due to centrifugal forces heavy particles were ejected from the vortex core. The relevant time for the deflection of the particles is the time delay between first and second pulse of the laser-light sheet. With a time delay of 2 $\mu$s, which was the maximum used delay, the deviation was 0.045% versus fluid flow in radial direction and 0.027% regarding the angular velocity.

Summing up, it has to be pointed out that accurate PIV measurements can be done in supersonic flow, when small tracer particles are used. The used oil aerosol is a compromise solution of the flow tracking capabilities and the amount of scattered light.

4.3 Velocity and Vorticity Distribution.
Figures 7 and 8 show the velocity and vorticity distribution over the leeward side of the model of ELAC. Comparing figures 7a and 7b the increasing angle of attack causes rising vorticity in the area of primary vortex. The helical character of the flow is shown in figure 8a by the streamlines which are situated in the spiral vortex sheet of primary separation. The non-conical velocity components show also the enrollment of the flow into secondary vortex.

The velocity distribution of crossflow velocities at a Mach number 2 and 10° angle of attack is shown in figure 9. In comparison to incompressible flow a smaller primary vortex develops over the leeward side.

5. Conclusions
Separation and reattachment of the separated flow over the leeward side of a model of the hypersonic configuration ELAC was investigated using oil film technique. The size and position of the primary vortex was then examined by the vapour-screen method at a Mach number 2 and 10° angle of attack. With help of PIV the velocity distribution over the delta wing was measured in sub- and supersonic flow. The enrollment of the flow into the spiral vortex sheet of primary vortex was shown by that.

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References


