Experimental and Numerical Study on the Flow behind a TPS

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Abstract

Particle Image Velocimetry (PIV) is a powerful tool for the non-intrusive investigation of complex flow fields. The present paper describes Stereo PIV (SPIV) measurements of the flow field behind a counter-rotating ultrahigh-bypass fan turbine power simulator (CRUF-TPS), which have been performed at the low speed wind tunnel NWB of the German-Dutch Wind Tunnels (DNW). The experimental data was used for the validation of numerical codes using different turbulence models.

The aim of the study was the investigation of the turbulence and the shear flow mixing in the flow behind the CRUF-TPS. The experimental SPIV set-up was made up of two PCO4000 cameras (11 Megapixels), providing a very high spatial resolution, and a high power Nd-YAG double pulse laser with 380mJ per pulse output energy. The flow was seeded with DEHS particles with a diameter of about 1 µm. In two different planes all three components of a large number of instantaneous velocity vector fields were measured in forward scattering mode for several different flow and turbine conditions. The first plane perpendicular to the main flow with an observation area of 410 x 330 mm² was located 450 mm downstream of the TPS core trailing edge, the second plane with a size of 360 x 300 mm² was adjusted horizontally parallel to the main flow. In both cases, the shear layers between free stream, fan flow and core flow of the TPS could be observed. In order to determine the differences between periodic and non-periodic effects of the turbulence mixing in the shear layers, the PIV measurements were triggered both at a random point of time and phase-locked to a fixed blade position of the TPS fan. For the evaluation of the PIV images an iterative multi-grid cross-correlation method with image deformation was applied, with 32 x 32 pixels² final window size and a step width of 16 pixels in each direction, leading to instantaneous velocity fields with up to 43000 three-component-vectors. 700 to 1000 double images were acquired per test case, thus ensuring that convergence of the averages and RMS-values could be attained. For the first PIV set-up (light sheet perpendicular to the main flow), the main flow component of the flow vorticity could also be calculated. For some test cases, CFD calculations of the CRUF flow have been performed by using the DLR TAU-code. The focus of this investigation was to ascertain the influences of grid resolution, dissipation rate, grid geometries, and different turbulence models.

1. Introduction

Particle Image Velocimetry (PIV) is an advanced non-intrusive optical measurement technique, which allows the measurement of large numbers of velocity vectors in a flow field with high spatial resolution and within short wind tunnel run times [1], [2]. From these velocity fields it is possible to calculate averages and other related derivatives of aerodynamic significance, such as, for example, RMS-values and vorticity. The present paper describes a joint experimental and numerical study of industrial relevance on the characterization of shear flow mixing and turbulence in the wake of a counter rotating ultrahigh-bypass fan turbine power simulator (CRUF-TPS) at DLR. The Stereo PIV data was used for the validation of numerical codes using different turbulence models, since former CFD calculations [3] had suffered from the absence of a complete experimental data base.

2. Experimental Set-up

The Stereo PIV measurements have been performed in the low speed wind tunnel NWB of the
German-Dutch Wind Tunnels (DNW) in Braunschweig. The NWB is a continuous, atmospheric, low-speed wind tunnel with a maximum flow velocity of 85 m/s and a cross section of $3.25 \times 2.8 \text{ m}^2$. The present investigations were carried out in the closed test section at 28 and 66 m/s, i.e. at $\text{Ma} = 0.08$ and 0.19.

For the measurements of the flow field behind a counter rotating ultrahigh-bypass fan engine (CRUF), a turbine power simulator (TPS) was applied (Fig. 1). The two rotors of the fan, each with eight propeller blades, had a diameter of 254 mm, and were driven with compressed air by a four-stage turbine. The TPS was attached at an angle of 90° on a profiled strut, which was mounted on the floor of the test section (Fig. 2). The surfaces of the model and the pylon were blackened to avoid disturbing reflections of the laser light.

![Fig. 1 Sketch of CRUF-TPS (longitudinal section)](image)

The beam of a high power Nd-YAG double pulse laser with an output energy of 380 mJ per pulse and a wavelength of 532 nm was directed by two tilted mirrors to the side wall of the test section, where it was expanded by two cylindrical lenses to the light sheet and brought through a 10 cm slit into the test section (Fig. 3). Due to the strong mechanical vibrations of the wind tunnel, the upper mirror and the lenses had to be attached to an X95 girder, which was standing on the foundation of the wind tunnel building.

![Fig. 2 CRUF-TPS with strut (left), front (middle) and back view (right)](image)
For the first SPIV set-up, the light sheet was positioned perpendicular to the flow 450 mm downstream of the TPS core trailing edge (Fig. 4, view is in flow direction). Its thickness was approx. 2.5 mm. In order to investigate the shear layer development between free stream, fan flow and core flow, a second SPIV set-up was used with a nearly horizontally positioned laser light sheet parallel to the main flow and between 10 and 310 mm downstream of the TPS core trailing edge (Fig. 5). Here, the thickness of the light sheet was approx. 1.5 mm.
In order to carry out the SPIV measurements in forward scattering mode with a very high spatial resolution, two PCO4000 cameras with 11 Megapixels were positioned at the opposite side wall of the test section. Similar to the light sheet optics, the cameras were also mounted on a girder standing on the building floor in order to avoid the vibrations of the wind tunnel. The laser light sheets could be observed through small holes in the side wall, using lenses with a focal length of 180 mm.

For the first SPIV set-up, the cameras were located at the same height of 1.2 m above the floor of the test section and about 1.1 m downstream and upstream of the light sheet. Thus, an observation area of 410 x 330 mm² perpendicular to the main flow could be achieved, comprising the wake of the TPS including the pylon and the model support (Fig. 6).
In the case of the second SPIV set-up, the two cameras were positioned vertically on top of each other at a distance to the light sheet of 943 mm (top camera) and 798 mm (bottom camera), yielding an observation area of 360 x 300 mm² parallel to the main flow with a small deviation of 0.6° from the horizontal position (Fig. 7). In this manner, the whole interesting region with the shear layers of free stream, fan flow and core flow could be observed.

![Fig. 7 Position of second SPIV observation area (view against flow direction)](image)

Due to the oblique observation directions (58° for the first, 54° and 59° for the second set-up), Scheimpflug adapters had to be mounted between cameras and lenses to achieve a continuous sharp image on the CCD chips [4].

For the seeding of the flow, an aerosol generator produced Di-ethyl-hexyl-sebacate (DEHS) particles (diameter ≈ 1 µm), which were injected downstream of the test section. After only a few circulations in the closed circuit of the wind tunnel, the particles were homogeneously distributed in the air over the observed regions of the light sheets. In addition, DEHS particles were added to the compressed air driving the TPS turbine in order to provide the TPS core flow with seeding particles.

### 3. Measurement Program and Evaluation

For each SPIV set-up, measurements at two different Mach numbers (Ma = 0.19 and 0.08) and two different rotation speeds (7400 and 6000 rpm) of the TPS fan engine have been performed. In order to analyze the differences between periodic and non-periodic effects of the turbulence mixing in the shear layers, the PIV measurements were triggered both at a random point of time (“random trigger”) and phase-locked to a fixed blade position of the TPS fan (“phase trigger”). Per test case of this measurement matrix, a number of 700 to 1000 double images were acquired thus ensuring that convergence of the velocity averages and RMS-values could be reached.
For the evaluation of the PIV images an iterative multi-grid cross-correlation scheme with image deformation was applied, starting with an interrogation window size of 96 x 96 pixels and a final window resolution of 32 x 32 pixels. The step width between the interrogation windows was 16 pixels in each direction (equivalent to 1.8 mm for the first and 2 mm for the second PIV set-up), leading to instantaneous velocity vector fields with more than 43,000 three-component-vectors each (27,500 for the second set-up). After evaluation of the instantaneous PIV images, for each test case the mean value and the standard deviation (RMS-value) for each of the three velocity components were determined. In addition, for the first SPIV set-up, the main flow component of the flow vorticity was also calculated from the mean values of the velocity field.

4. Experimental Results

Fig. 8 shows the result of a SPIV measurement for the first laser light sheet perpendicular to the main flow (see Fig. 6) averaged over 760 randomly triggered samples for Ma = 0.19 and a TPS fan rotation speed of 7400 rpm. The magnitude of the local velocity vectors is color-coded, where turquoise corresponds to the main flow velocity of 65.5 m/s. The measurement shows that the fan jet is accelerated up to 106 m/s and its profile is shaped by the struts inside the fan nozzle. Obviously the pylon exerts a significant impact on the wake of the fan jet, whose velocity varies here only between 65 and 75 m/s. This also applies to the free stream, which is decelerated to 42 m/s behind the transition from pylon to model support (blue λ-shaped structure): The flange seems to cause a separation of the flow. The core jet (simulated jet wash) is clearly depicted, having a flow velocity of about 45 m/s.

For the same test case, Fig. 10 shows the magnitude of the RMS-values (standard deviation) of the averaged velocity vectors. As expected, the velocity of the outer undisturbed main flow fluctuates by at most 0.5 m/s, corresponding to a degree of turbulence of less than 1%. In contrast the RMS-values in the region behind the support flange increase to 24 m/s, indicating again the separation of the flow. The fluctuations in the shear layer between core and fan jet are also relatively large, varying from 15 to 19 m/s. The RMS-values of the fan jet are between 5 and 10 m/s, their distribution being influenced by the struts inside the fan nozzle.
Fig. 10 Magnitude of RMS-values
Ma = 0.19, 7400 rpm

Fig. 11 Main flow component of vorticity
Ma = 0.19, 7400 rpm

Fig. 12 Random trigger
Magnitude of averaged 3-component velocity vector field at Ma = 0.19 and 7400 rpm

Fig. 13 Phase-locked trigger

For the second SPIV set-up the measurement area was aligned parallel to the main flow intersecting core and fan jet and the flow around the nacelle (see Fig. 7). Fig. 12 shows the color-coded magnitude of the three-component velocity vectors calculated by averaging 1000 randomly triggered samples. Again the fan rotation speed was 7400 rpm and the main flow velocity Ma =
0.19, i.e. 66 m/s (green color). The PIV data shows clearly the blue core jet with a minimum velocity of 27 m/s and the violet/red regions of the fan jet (up to 112 m/s). Also the turbulent shear layers between fan and core jet as well as the shear layers between fan jet and undisturbed flow around the nacelle can easily be observed. Whereas the left part of the fan jet decelerates in downstream direction, maintaining its thickness, the right part broadens downstream.

In order to distinguish the periodic parts in the flow for the same test case, 700 SPIV measurements have been performed with a trigger phase-locked to a fixed blade position of the fan. The averaged magnitude of the velocity vectors is shown in Fig. 13. In comparison to Fig. 12 (“random trigger”) it is remarkable that the shear layer between fan jet and the outer flow exhibits a wavy modulation, which is due to the influence of the rotor blades. This wavy structure can also be observed in the shear layer between fan and core jet, albeit to a lesser extent.

In the same way the periodic and non-periodic parts of the flow in the shear layers can be distinguished by calculating the standard deviation of the averaged velocity vectors. Fig. 14 shows the magnitude of the RMS-values for the “random trigger” case (same test conditions as in Fig. 12), and Fig. 15 for the phase-locked case (same as in Fig. 13). The shear layer between left fan jet and core jet (red strip) exhibits with up to 19 m/s a strong turbulence, its counterpart with the right fan jet (yellow strip) at least up to 15 m/s. Whereas the shear layers in the “random trigger” case possess a smooth structure, they exhibit in the phase-locked case a modulated structure in downstream direction, similar to the shape of a pearl necklace. This difference can be observed even more explicit in the shear layer between right fan jet and outer flow: whereas in Fig. 14 the shear layer is smooth and continuous, Fig. 15 shows spots of alternately lower and higher turbulence.

![Fig. 14 Random trigger](image1)

![Fig. 15 Phase-locked trigger](image2)

**Fig. 14** Random trigger

Magnitude of RMS-values of averaged 3C velocity vector field at Ma = 0.19 and 7400 rpm

**Fig. 15** Phase-locked trigger

**5. Numerical Results**

For some test cases, CFD calculations of the flow behind the CRUF-TPS have been performed by using the DLR TAU-code [5]. The wind tunnel set-up of the CRUF simulator, as shown in Figs. 2 and 5, was rebuilt in CATIA [6]. Based on the surface geometry description, hybrid grids were generated by applying the commercial software package Centaur from CentaurSoft [7]. Special
effort was spent on manually refining the grid in regions of high flow gradients. In addition, grid adaptation of the TAU-code was used to further increase grid quality. The focus of investigation was to clarify the influences of grid resolution, dissipation rate, grid geometries (tetra-/hexagonal) and different turbulence models. The one-equation turbulence model of Spalart-Allmaras [8] and the two-equation turbulence model k-ω-Menter SST [9] were applied in a first step. The computations have been performed assuming fully turbulent flow conditions. The results of the one-equation model showed shortcomings in the resolution of the mixing layers. Good results were obtained with the k-ω-Menter SST model, including the prediction of separated flow appearing at the strut and half wing geometry opposite to the nacelle, the same as was measured experimentally. Due to the occurrence of flow separation and the applied local time stepping method, convergence problems became apparent, pertaining especially to density residuals, indicating slight unsteady effects. Similar results were obtained by applying a Reynolds-Stress-Model [10], which accounts for anisotropic turbulence. However, the results could not be significantly improved.

As an example, the CFD result of a TAU-code simulation using the k-ω-Menter SST turbulence model is depicted in Fig. 9, showing good agreement with the corresponding SPIV measurement (Fig. 8).

6. Conclusions

The measurements in the wake of a CRUF-TPS have demonstrated that high resolution Stereo PIV is a powerful tool for the investigation of flow fields even with a high degree of turbulence. For the present investigations up to 1000 instantaneous SPIV measurements have been performed per test case, each yielding up to 43,000 three-component-vectors of the velocity field. The capturing of the SPIV images by a phase-locked trigger at a fixed fan blade position allows the discrimination between periodic and non-periodic properties of the flow field. The experimental results are of sufficient and comprehensive enough so that they can be used for the validation of CFD codes, especially for the testing of turbulence models. Together, the experimental and numerical results provide detailed insights into the various flow structures behind a CRUF-TPS.

References


4. Scheimpflug T (1904) Improved Method and Apparatus for the Systematic Alteration or Distortion of Plane Pictures and Images by Means of Lenses and Mirrors for Photography and for other purposes, UK Patent No. 1196


