In-flight flow visualisation using Particle Image Velocimetry

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Abstract
Applying advanced non-intrusive flow visualisation techniques to an in-flight environment is a challenging task which can provide invaluable data. The ability to capture complex flow structures under free atmospheric influences and in real flight conditions can potentially supply data for validation of numerical simulation and comparison to wind tunnel measurements. Within the scope of an European research project several optical methods have been implemented to different types of aircraft to test their feasibility during flight or ground based investigations. This paper reports on the installation of a modified PIV setup inside a DLR research aircraft and the subsequent PIV flight tests. During the project a number of certification procedures were required. PIV laser systems in general are hazardous in their operation and high safety standards have to be defined. These provisions lead to operational restrictions during flights. The arrangement of the experimental procedure was specified and certified for a Dornier DO 228-101 aircraft by the German Aerospace Center (DLR) together with Cranfield University. Furthermore, the use of standard PIV seeding generators in-flight is not a practical option. An alternative approach has shown a good way to provide viable seeding: flying through natural aerosols – such as those in clouds. Hence, this paper will report on the preparation, challenges of the installation of a modified PIV setup inside a small research aircraft and the subsequent PIV flight test results.

1. Introduction
A thorough investigation of the aerodynamics of an aircraft during its design phase is based on a combination of wind tunnel measurements and numerical simulations. The subsequent problem of extrapolating all those data to the real flight has been with the designers and developers of aircraft since the very beginning of aviation. Unpredictable or poorly understood limitations of wind tunnel measurements or numerical simulations with slightly different geometrical dimensions as well as disturbing effects of the mounting systems or the lower Reynolds number can lead to a new type of aircraft falling short of its predetermined and promised performance. Hence, flight tests with the full scale aircraft are almost mandatory to justify the aerodynamical and flight mechanical parameters obtained during experimental or numerical simulations. In this context, capturing velocity vector fields of the flow around an aircraft during free flight conditions is a basic but challenging task. In order to avoid influences of sensor systems exposed to the flow, non-intrusive measurement techniques are desired. However, reliable whole field techniques for a precise quantification of the aircraft flow have not been available for real flight environments up to now. The fields of application of such tools could be the measurement of a broad variety of different aerodynamical phenomena having a major impact on the aircraft performance (e.g. wing and fuselage boundary layer flow and separation, vortical flow, shock detection, propeller slipstream).

Several attempts in the past were dealing with the implementation of flow visualisation and measurement techniques for flight testing. Fisher et al [1] presented an assembly and evaluation of several flow visualisation techniques for flight research divided into their field of application (e.g. boundary layer transition, shock visualisation, vortical flow). The flow visualisation was mainly based on flow cones, tufts, oil flows, liquid crystals, sublimating chemicals and emitted fluids. Brandon et al [2] used surface (oil coatings) and off-surface flow visualisation techniques (vapour
screen system with a light sheet) in order to detect a three dimensional vortex system on an aircraft with vortex flaps. The results were compared to experimental and theoretical studies to verify these design tools. The outcome indicated that small geometric perturbations on the real wing were causing a very complex and significantly different flow as predicted by CFD or wind tunnel models. This particular example case underlines the importance of flight testing.

Going one step further means not only to visualise but also to quantify the nature of the flow around an aircraft with the help of flow measurement techniques such as Laser Doppler Anemometry (LDA) or Particle Image Velocimetry (PIV). In this respect Becker et al [3] presented an airborne LDA system for in-flight boundary layer investigations of a small aircraft wing. Within these experiments the difficulties coming along with the dependency on viable scattering particles in the atmosphere were tackled. Hence, the LDA system design was driven by the maximisation of the measured signal generated by particles with a diameter less than approximately 1 µm. A similar system also based on LDA was developed by Grosche et al [4] and described by Jentink et al [5]. The main purpose of those flight test techniques were a contribution to the aircraft air data systems for e.g. airspeed measurements.

The recent European research project AIM (Advanced In-flight Measurement Techniques) adapted mature optical measurement techniques to standard tools for flight testing. As method to measure velocity fields the Particle Image Velocimetry (PIV) has been chosen. Nowadays, this experimental technique is used for a wide range of scientific applications in wind tunnels [10]. It has the ability to record the information of complete instantaneous flow fields with a high spatial resolution. This feature makes PIV suitable for the investigation of high speed or unsteady flow fields. Still a number of challenges have to be faced when applying PIV to in-flight testing, such as: observation areas, time constraints given by the utilisation of the aircraft, interactions of the measurement systems, strongly changing environmental parameters during the flight, vibrations and atmospherical turbulences, accessibility inside the aircraft as well as high safety precautions for the laser operation [6]. Nevertheless, the PIV technique promised to be an attractive tool in this type of application with its ability to capture velocity vector field information containing a wide range of spatial scales in the flow. Moreover, the PIV technique can provide a significant amount of experimental data for the validation of numerical flow simulations. For all these reasons, PIV was the method of choice for investigating the complex flow fields in selected planes around an aircraft.

This paper presents an approach on the integration of a PIV system to a small research aircraft flying within the subsonic regime. Challenges as well as achievements are described and discussed. Furthermore, the paper will close with a brief outlook of the present activities and future objectives.

2. Experimental Methodology, Approach and Final Setup

The PIV technique is based on imaging tracer particles (i.e. seeding) in the flow of interest which are illuminated by a pair of laser light pulses in a plane of the flow. These laser light sheet planes are usually oriented normal to the imaging axis of the camera. The camera system captures the scattered light of the particles at times t and t' either on a single frame or on two separate frames. The velocity information is then derived from the displacement of the tracer images, the time delay between the two laser pulses and the magnification of the imaging system. The evaluation of the pair of PIV images captured at times t and t' is based on an auto- or cross-correlation algorithm applied within small interrogation windows. Extending the PIV system to a stereoscopic camera setup enables the determination of all three components of the instantaneous velocity vectors in a plane of the flow. The stereoscopic camera setup consists of at least two cameras observing the same area illuminated by the light sheet under different viewing angles.

Integrating a PIV system to an in-flight environment causes several problems. On one hand, a number of certification procedures have to be pursued to ensure safe operation in all conceivable
flight conditions. The necessary laser systems are hazardous in their operation and high safety standards have to be defined to tackle the risks. These measures result in restrictions to the operational limits during the flight. To avoid health risk caused by the laser light pulses everyone on board of the aircraft has to wear laser safety goggles during laser operations. These goggles restricted the visual perception of the pilots and hence, only flights according to visual flight rules and under daylight conditions were allowed. But, bright background illumination has a negative influence on the PIV images due to a constant overexposure of the second frame captured by the CCD sensors of the full frame camera system. This circumstance could be avoided by flying close to dusk or dawn where the visual flight rules are still allowed to be applied but the sunlight influence is quite low.

In general, performing flight tests with a research aircraft usually requires different configurations for each flight test campaign, so that the aircraft has to be modified often. Therefore, the DLR set-up a DLR Design Organisation which is approved by the German Airworthiness Authority (Luftfahrtbundesamt, LBA). This approval enables DLR to handle minor changes on its own research aircraft without involvement of the LBA. The flight test installation of the in-flight PIV campaign was classified as a minor change of the Research Aircraft Do 228-101 D-CODE (see Figure 1, Left). All equipment had to be qualified according to the requirements of Federal Aviation Regulations (FAR) to receive a Permit-to-fly from the DLR Airworthiness Office. In this particular case, the certification of the experimental setup inside the aircraft cabin comprises static stress analysis of all installed devices, laser safety assessments, definition of the cabin layout as well as an approval of the electric connection of all components including power supply provided by the generators of the aircraft engines [6]. The whole certification phase lasted more than 3-4 months and was an indispensable part of the whole measurement campaign.

![Figure 1: Left: Research aircraft Dornier Do 228 – 101 with the sketched laser light sheet](image1.png)

![Figure 1: Right: Typical Stratocumulus cloud layer during the test flight](image2.png)

On the other hand, the availability of feasible tracer particles is a crucial factor for the success of a PIV measurement. The PIV method requires tracer particles following the accelerations within the flow without any lag in order to determine the local velocity vectors indirectly with the help of the particle displacements. To guarantee a consistent set of velocity data without outliers, a high density and uniformly distributed seeding in the field of view is necessary. This demand becomes increasingly challenging in regions with strong recirculation or with high velocity gradients. A common way to seed the flow in wind tunnels is the installation of bespoke aerosol generators which are able to inject the seeding (e.g. oil droplets, glass micro-balloons) precisely into the test section. However, during the flight test an additional installation of the output devices of a seeding generator outside the aircraft and upstream the region of interest would not only disturb the flow but also be very difficult to attach to the external aircraft structure. Additionally a homogeneous distribution of particles along short distances is only possible in turbulent flows e.g. turbulent boundary layer. Hence, another approach has to be pursued. In this case, for the first time with PIV,
natural particles in the atmosphere from clouds were used, see Figure 1, Right.

Due to the fact, that this flight test campaign was defined as a feasibility study, the PIV setup was based on a commonly used and well approved assembly of PIV components to avoid any additional complications. In general, a PIV system consists of five sub systems: illumination, imaging system, particles (i.e. seeding), evaluation software and post processing software. Hence, the most challenging task for this particular project was to adapt and apply all these sub systems to an in-flight environment.

The PIV setup consists of two PCO 1600 cameras mounted on a support in a stereoscopic alignment. The camera provided an image resolution of 1600 x 1200 pixels and a field of view of around 68 x 90 mm² defined by the particular imaging system itemised in Table 1. The light source for the illumination of the seeding particles was provided by a double cavity Nd:YAG laser system. The used CFR 400 laser was designed by Big Sky/USA to meet the requirements of different fields of application. The design was mainly driven by an operation under severe and harsh environments. The laser system itself is shock and vibration tested and therefore likely to be resistant against the aircraft vibrations during flight or taxi. In addition, the laser case is very compact and cooled by air (i.e. independent of external water supply). The laser was triggered with a repetition rate of 10 Hz and a pulse energy – exposed over a pulse duration of 9 ns - each of 200 mJ (@ 532 nm green light). A sequencer synchronised the laser pulses and camera frame shutter. The laser system and its control units as well as the camera power units and the sequencer were installed inside a 19” rack in the rear part of the aircraft cabin (see Figure 2). The light sheet optics (which expanded the laser light to a vertical light sheet) were attached to the laser and pointed into a convex window. A laboratory study prior to the first flight test assessed the influence of the laser light to the material of the spherical window and vice versa and found no damage on the window surface nor severe optical aberrations of the laser light sheet due to the window curvatures.

Table 1: PIV recording parameters

<table>
<thead>
<tr>
<th>Flow structure characteristics:</th>
<th>aircraft velocity: 55-95 m/s (Re ~ 3·10^7), outer fuselage boundary layer, propeller slipstream, flap downwash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of view:</td>
<td>68 x 90 mm²</td>
</tr>
<tr>
<td>Observation distance:</td>
<td>~ 120 mm</td>
</tr>
<tr>
<td>Recording method:</td>
<td>1st &amp; 2nd flight test: single frame/double exposure</td>
</tr>
<tr>
<td></td>
<td>3rd flight test: double frame/single exposure</td>
</tr>
<tr>
<td>Recording medium:</td>
<td>digital 14 bit CCD camera system – 1600 x 1200 pixel</td>
</tr>
<tr>
<td>Recording lens:</td>
<td>f = 21 mm</td>
</tr>
<tr>
<td>Illumination:</td>
<td>Nd: YAG Laser – 200 mJ/pulse (@ 532 nm (double pulse))</td>
</tr>
<tr>
<td>Pulse delay:</td>
<td>Δt = 10 μs</td>
</tr>
<tr>
<td>Seeding material:</td>
<td>natural aerosols / cloud droplets</td>
</tr>
</tbody>
</table>

The PIV system was installed into the Dornier Do 228 research aircraft of the DLR Braunschweig / Germany. The Do 228 possesses STOL (Short Take-Off and Landing) abilities and two turboprop engines with high power generators which were required for the laser operation during the flight. The experimental use of the Do 228 at the DLR varies from several aerodynamic to flight guidance measurement campaigns. One of the most important features supplied by this aircraft for this particular flight test was the unpressurised cabin in combination with the permanently installed spherical window. This window enabled an alignment of the laser light sheet parallel to the fuselage and hence provided the option of an optimal viewing angle for the cameras.
3. Tracer Particles

As discussed previously, the only viable seeding source for this particular flight test were atmospheric particles with a distinct size distribution, e.g. cloud droplets. In short, cloud formation is based on the condensation of moisture on hygroscopic nuclei. These nuclei are microscopic particles called aerosols with wettable and soluble properties e.g. dust, sea salts, smoke and chemical components [7]. The diameter of cloud particles vary between 0.1 µm (condensed core) and approximately 10.000 µm (hail corns). Due to the restrictions defined by the laser system operation, the permitted altitude range of this particular flight test was between 900 and 3.000 m. However, the actual altitude of most of the measuring points was between 1.500 and 2.200 m. At these heights mainly low level clouds (0 - 2 km) and cloud types that are able to extend through all altitude levels (e.g. Nimbostratus Ns and Cumulus Cu) are formed, see Figure 4, Left. The lower clouds are most often specified as Stratus (St) and Stratocumulus (Sc) with mean radii of 2 - 40 µm [8].
Several studies in terms of scattered light intensities and acceptable particle velocity lag indicated that good characteristics are attained with a particle size of around 1 µm [9]. Particles with a diameter of around 5 µm are less able to follow the flow faithfully but possess an enhanced scattering behaviour [10]. Therefore, a certain slip velocity shall exist during the measurement which is hard to predict due to an unavailable reference measurement of the flow velocity. Some sample counting of the number of particles captured by one image indicated that around 10000 particles are found within one recording (see Figure 3). That means, based on the given image size and light sheet thickness of around 3 mm, approximately 540 cloud droplets/cm³ were detected in an average Sc or Cu cloud. These values are above what to expect in an average cloud layer of that kind. In addition, the size of the particle images seems to vary between 1 and 8 pixels. Hence, considering a pixel size of 7.4 x 7.4 µm² (PCO 1600 specification) leads to observed particle image diameters of around 7 - 60 µm. The diffraction limited imaging is causing a diffraction pattern (Airy rings) on an image sensor. This Airy disk represents the smallest diameter of the particles that the chosen imaging system can obtain. The magnification factor of the camera setup was M = 0.25 and the f-number f # is equal to the ratio between the focal length and the aperture diameter of the entrance pupil of the objective (f # = f/Da = 21 mm/7.3 mm = 2.8). The diffraction limited minimum image diameter is defined by: 

\[ d_{\text{diff}} = 2.44 \cdot f # \cdot (M+1) \cdot \lambda. \]

Knowing the wavelength of the incident light \( \lambda = 532 \text{ nm} \) the result is: \( d_{\text{diff}} = 4.54 \text{ µm} \). However, when recording larger particles (\( d_p > > \lambda \), Mie’s theory) the diffraction limit becomes less important and the impact of the particle’s geometric image \( M d_p \) increases. Assuming a negligible influence of the lens aberration yields a particle image diameter obtained by:

\[ d_p = \frac{\sqrt{d_r^2 - d_{\text{diff}}^2}}{M}. \]

As already stated, the observed particle image diameters varies between 7 to 60 µm. Hence, the particles diameter varies between: 20 and 240 µm. This derived size distribution seems to be more in accordance with meteorological observations and research studies [7] but less with required and expected particle images for a common PIV measurement. The impreciseness of these results is probably caused by the assumption of negligible lens aberration errors and the determination of the particles diameters extracted from PIV images. However, it cannot be excluded that a certain amount of particles inside a cloud have a diameter below 20 µm. Hence, the installed PIV system is able to record particles with a diameter of around 1 µm.

**Figure 4:** Left: Test aircraft diving into one Nimbostratus cloud layer  
Right: Mie scattering for a water droplet in air [11]

Beside the mechanical properties of a seeding particle, the light scattering behaviour is of equal importance. The light scattering and resultant image intensity depends on many factors including the refractive index of the particles to that of the surrounding medium, the particle diameter, the particle shape and its orientation [10]. The observed particles are believed to have an average radius of around 7 - 60 µm. These diameters are larger than the wavelength of the incident light.
\( \lambda = 532 \) nm. This means, that the light scattering at this kind of seeding occurs in the Mie regime. The scattering intensity over the cross section of a spherical particle strongly varies as a function of the scattering angle (see Figure 4, Right). For a water droplet in air most of the light is scattered in forward direction, but the experimental setup of this particular flight test recorded at a viewing angle of 90°. Nevertheless, evaluable PIV recordings could be obtained due to the small distance between the camera and the laser light sheet and the available laser power.

4. Flight Test Results and Analysis

A total of three flights were carried out in September 2009 departing at the Airport Braunschweig-Wolfsburg in Germany. The main purpose of the first flight was a general system check and functionality test especially with regard to the laser operation. The profile of all flights and the PIV data recording strongly depended on the location of sufficient cloud layers.

The outcome of the very first flight test was disappointing. The recordings presented a low quality because of an overexposure of the second frame and a large overexposed area in the first frame (due to the bright background illumination of the daylight) as well as strong fluctuations of the particle density inside the clouds. Only one recorded sequence of images turned out to be evaluable because of a higher cloud particle density which occurred while climbing through a thin Stratocumulus (Sc) cloud layer.

The second flight appeared promising as a large low pressure area, covering the southern part of Germany was generating different kinds of clouds rising through several altitude levels. The flight path was selected to reduce the impact of the bright sunlight on the camera frames. The overall outcome of this flight were seven measuring conditions with different aircraft parameters, such as changing velocities and flap settings at an almost constant altitude level. Nevertheless, the brightness of the daylight was still causing an overexposure of the second camera frame. One way to overcome this problem was by illuminating the first frame twice by the laser (shutter time 200 \( \mu \)sec). These single frame/double exposure images were then evaluated with the autocorrelation technique. This technique is still the first choice when using photographic film or single frame digital cameras. In principle, the autocorrelation technique is based on the fact that a single recording contains two or more exposures of the same particle. A major drawback of this method is the ambiguity of the particle direction because the recorded frames provide no information about the actual sign of direction of the particle displacement. Fortunately, in this particular case the direction of the flow was clearly given through the unambiguousness of the approaching flow passing from left to right of the window. Hence, the assumption was made, that the right peak of the correlation plane of the double exposed recording was the displaced one. This approach was employed to all acquired images of the first two flights which were affected by the bright daylight conditions. For future measurement campaigns, additional hardware components like beam splitter, mechanical or LCD shutter might be considered to reduce the background illumination as well and employ the more accurate double frame technique. Depending on the requirements for the system, the advantages and disadvantages of those devices shall be deliberated carefully.

Nevertheless, to further improve the signal quality, a third flight was conducted. This time the aircraft took off for a short flight close to dusk. The stereoscopic recordings obtained in this case showed promising results because both frames resp. particle illuminations have a sufficient signal-to-noise ratio, so that the cross-correlation technique could be applied.

During the evaluation of the PIV images an interrogation window size of 48 x 48 pixels and a step size of 16 x 16 pixels (66 \% overlap) was used in conjunction with both – an autocorrelation (flight test no. 1 & 2) and cross-correlation (flight test no. 3) algorithm. In addition, a multi pass interrogation with 3 interrogation passes was deployed to the data set of the first two flights in order to reduce the bias – error and increase the data yield. For the image sequence of the third flight the
multigrid interrogation with image deformation was chosen. This interrogation method is starting off with larger interrogation windows (128 x 128 pixels) and refines the windows and grids subsequently with each pass (final window size in this particular case: 48 x 48 pixels). Applying these evaluation settings to all usable images (depending on the algorithm) generated a sequence of flow structures as present in the vicinity of the aircraft. A sample of two subsequent images ($\Delta t = 0.1$ s) is given in Figure 5. These evaluated images indicate a strong fluctuation of the flow. The sequence was recorded while flying 75 m/s and with flaps retracted (clean configuration). One reason for this apparent turbulence could be that the flow area imaged, 68 x 90 mm², was within the turbulent boundary layer on the aircraft fuselage. In addition, the influence of the propeller slipstream and flap on the flow in this region is unknown and due to the propeller rotation, these effects would be highly periodic with no synchronisation with the PIV data. Recording further inspection of the data showed that the flow properties changed slightly depending on the aircraft settings. One data set from the second flight test with an indicated airspeed of $v_{\text{IAS}} = 57$ m/s and maximum flap settings showed a higher downward component of flow but also a lower relative velocity fluctuation within each single velocity vector field.

![Figure 5](image_url)

*Figure 5: Two subsequent images ($\Delta t = 0.1$ s) at $v_{\text{IAS}} = 75$ m/s and with flaps retracted (3rd test flight)*

The most valuable results were obtained during the third test flight. Here, although the captured velocity data (altitude $H = 1500$ m, $v_{\text{IAS}} = 75$ m/s, clean configuration) do not provide new knowledge about the physics of the flow, the PIV image quality in this case was high enough to confirm proof of principle of the PIV technique for flight test. Figure 6 presents the obtained displacements over a sequence of 160 PIV images. Considering a pulse delay of the laser light with $\Delta t = 10$ $\mu$s and the magnification factor of 16 pixels/mm yields the converted velocities for the given displacements. The main direction of the flow is given along the x-axis. At this, most particles show a displacement of around 11.8 pixels (~74 m/s) and in general a slightly wider variation of the displacement values (3 pixels). In y direction most of the displacement vectors seems to tend to turn to negative values even though only with small magnitudes (0.8 pixels ~5 m/s) combined with a generally small variation of the displacements (~2 pixels). This betokens a stronger downwash of the flow. The out of plane component in z-direction indicated the most distinct results. The displacements are quite small (0.2 pixels ~1.25 m/s) compared to the x-direction and are pointing out, that there is a weak velocity component pointing
towards the fuselage (positive z-direction). The maximum is clearly developed and indicated a very homogeneous velocity normal to the field of view. In general, all three graphs show no sign of peak locking [12]. Peak locking is caused by an unfortunate choice of the peak-fitting algorithm in combination with typically too small particles image sizes (< 1 pixel). The outcome is a tendency of the algorithms to lock into integer values. In this case the histogram will show a number of integer-spaced peaks. In this regard, the given graphs show no sign of peak locking. The small oscillations close to the peak of the first histogram were caused by a too coarse step size of the evaluation process and the limited number of realisations (based on ~ 160 PIV images).

Figure 6: Histograms for all three dimensions

4. Conclusion & Outlook

This paper, the authors believe for the first time, has presented high quality PIV data from a PIV setup for use in in-flight tests. The proof of principle tests, using a Dornier Do228 aircraft and ruggedised PIV equipment, were conducted over three research flights in order to obtain a comprehensive set of PIV images which were successfully analysed. Although no distinct flow structure could be verified in relation to the position of the measurement plane in the flow, the feasibility of the PIV measurement method for the determination of in-flight flow phenomena has been demonstrated. The problems that occurred during the preparation and flight test have identified the most critical limitations for future flight tests.

For future flight tests, there still remain a number of issues that must be resolved in order to increase the potential of the PIV in-flight technique. One of these is the dependence on natural cloud aerosols as PIV seeding under high velocity conditions, in constantly changing altitude levels (independency of clouds) and the challenge for reliable results that these conditions present. Hence, an extended study of artificial and natural seeding possibilities is currently in progress as well as the preparation of the certification process for upcoming flight tests. Some minor changes of the already tested setup have to be adapted and approved for their safe operation during flights. In addition, some optimisation of the hardware installation shall be considered due to the complex restrictions for airborne laser operation. Two shuttered camera frames should be used in future PIV flight tests by combining the sensor planes of two cameras via a beam-splitter cube. This would allow PIV measurements in cross-correlation modus even during daylight.

Once these challenges have been addressed, PIV has the potential to provide a powerful in-flight technique to allow the study of fundamental and applied aerodynamic phenomena. To this end, future projects aim to convey the gathered experiences to e.g. flight test for certification or boundary layer flow characterisation.
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