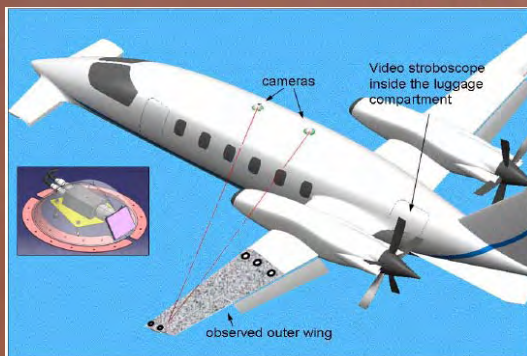


ADVANCED IN-FLIGHT MEASUREMENT TECHNIQUES

Specific Targeted Research Project

An Overview



Toulouse, November 2008

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AIM – A New Approach for In-Flight Measurement Techniques

The European Specific Targeted Research Project (STReP) *AIM – Advanced In-Flight Measurement Techniques* was launched on November 1, 2006. This project intends to make advanced, non-intrusive measurement techniques applicable for time and cost effective industrial flight testing as well as for in-flight testing for research. In the AIM consortium, eleven Partners from aircraft industries, airport services and research organizations from 7 countries are working closely together. These partners are: Piaggio Aero Industries (I), Eurocopter France (F), Eurocopter Deutschland (D), Airbus France (F), DLR (D), ONERA (F), NLR (NL), EVEKTOR (CZ), Flughafen Braunschweig Wolfsburg GmbH (D), Cranfield University (GB) and MPEI-Technical University (RUS).

AIM is coordinated by DLR in Göttingen, where Mr. Fritz Boden¹ functions as the coordinator of this 3.6 million Euro STReP.

The purpose of the 3-year AIM project is to further develop optical measurement techniques in such a

way that they can be routinely applied to flight tests, hence providing comprehensive planar information on various important parameters such as wing and propeller deformation, thermal loads on the structures of helicopters, the surface pressure distribution on a wing, density gradients of strong vortices generated by airplanes and helicopters and velocity flow fields near airplanes and helicopters.



All measurements will be carried out in full-scale outdoor flight tests on 5 aircraft (VfW614 ATTAS, Dornier Do 228, Piaggio P180, Fairchild Metro II, Airbus A380) and 3 helicopters (Eurocopter EC-135 ACT/ FHS, Eurocopter Superpuma, MBB Bo 105).

During the last two years, several measurement setups have been designed for this purpose and some of them have already been tested on the aircraft e.g. wing and propeller defor-

mation measurements with the Image Pattern Correlation Technique (IPCT) on the Piaggio P180 and the Fairchild Metro II.

In the following pages an overview of the advanced optical measurement techniques tested within AIM for in-flight application will be given.

The measurement principles of the techniques PIV (Particle Image Velocimetry), BOS (Background Oriented Schlieren method), IPCT (Image Pattern Correlation Technique), QVT (Quantitative Video Technique), LiDaR (Light Detection and Ranging method), PSP (Pressure Sensitive Paint) and IRT (Infra Red Technique) are briefly described. Some sample applications are given to show the potential of these techniques.

The AIM project clearly demonstrates innovative possibilities of a joint multi-national cooperation between aircraft industries and research organizations. The EU-funded project will end in October 2009, but during the work in this project a multitude of demanding in flight applications for non-intrusive measurement techniques have been identified which will have to be addressed in future.

¹ He is the successor of Dr. Falk Klinge who left the DLR in December 2007 and whom we want to thank for his great job at AIM.

Particle Image Velocimetry (PIV)

Making the first move for an in-flight PIV application

Particle Image Velocimetry (PIV) is now a mature measurement technique for the investigation of complex instantaneous and mean planar flow fields in a plane of interest in a seeded fluid flow. The range of application of the PIV technique has expanded widely and is now able to cover many different research areas, including micro- and supersonic flows. However, there is still the necessity for further development and extension of the PIV technique, for example, for larger scales. For this reason the AIM project dedicated itself to the investigation of the feasibility of the PIV technique to ground based and in-flight experiments.

In its simplest form, a pulsed laser light sheet is placed in the seeded fluid and a pair of particle images is recorded using a digital camera perpendicular to the light sheet. The time interval between the two laser pulses is substantially smaller than the flow timescales studied. The PIV image pairs are

subsequently processed using spatial correlation techniques to yield 2D instantaneous vector fields which can also be summed to generate an average fluid flow map. Extension of the technique to three dimensional (3D) measurements is possible by using a pair of imaging cameras in a stereoscopic PIV

arrangement. Recent developments of this technique use multiple camera setups to tomographically image a fluid volume to yield the full 3D vector map. Where 2D or 3D data are required, complete commercial systems are available for both the imaging and data processing of PIV.

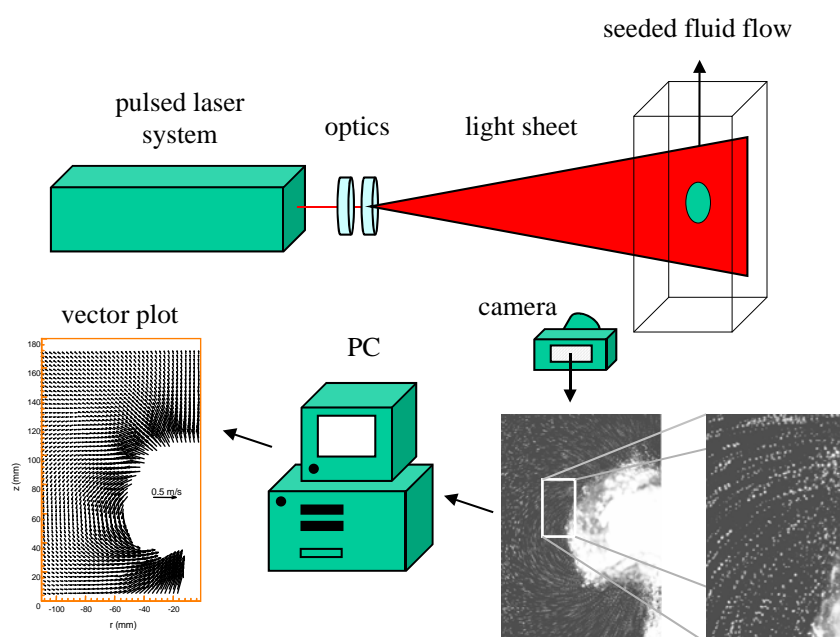
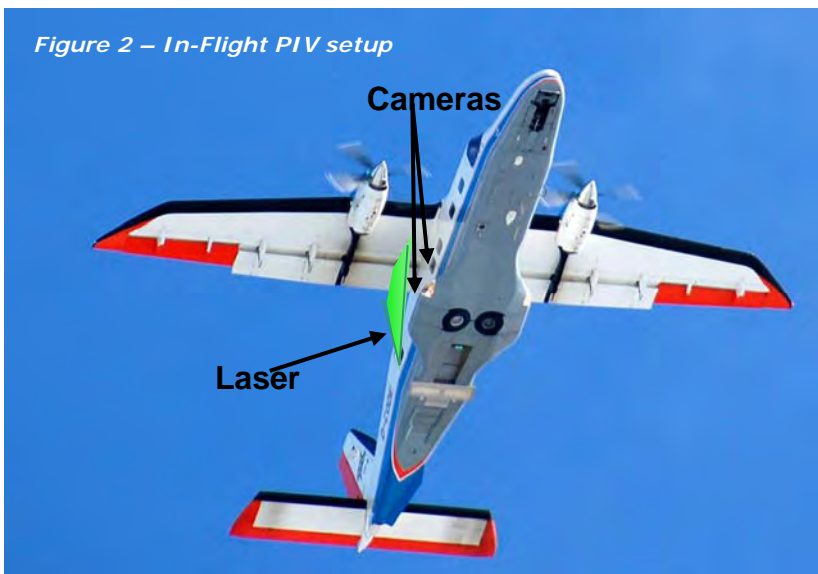


Figure 1 - Basic principle of 2D PIV technique

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Within the scope of the AIM project two different applications of the PIV technique were investigated. On the one hand a ground based PIV setup aims to capture the high-lift vortex structures of a low flying-by aircraft (approach configuration). This kind of experiment will be carried out by the DLR with the help of the Airport Braunschweig-Wolfsburg (EDVE). Figure 3 gives a brief insight into the future ground-based flight tests. This experimental setup foresees the use of a laser sheet which is expanded in a vertical direction to the runway. The seeding generator must be able to produce a large and homogenous amount of tracer particles (e.g. stable soap bubbles) covering the observation area on the runway. Several cameras, positioned at suitable locations, capture the scattered light of the illuminated particles at different time steps. The obtained data will help to determine the size, propagation and strength of the wing vortex close to the ground.

On the other hand an advanced in-flight PIV arrangement (Figure 2) has been specified by Cranfield University and DLR to measure the complex flow structures of the aircraft



over a certain range of flight conditions. A number of possible options for the PIV setup inside the aircraft has been considered in the AIM program and the best solution established involves the mounting of the laser and camera inside the aircraft. This option does not require window modifications and would be operable inside both pressurized and unpressurized aircraft cabins. Prior to operation inside of the pressurized aircraft, ground tests on the window have been conducted with the laser to ensure the integrity of the window material under Class IV laser exposure. In the long run, this approach shows promise for flow observations in a near free stream environment.

However, a number of challenges have to be met before PIV can be applied to outdoor ground based and in-flight measurements. Besides the determination of the distinct aircraft/airfield setup and the laser safety configurations, the most crucial issue involves the amount of seeding (small tracer particles) required for PIV during these tests. Seeding specifications for PIV are critical both for data output quality and the imaging system requirements. In a research environment seeding particles are artificially introduced into the fluid system in a controlled manner using special seeding apparatuses. Common seeding particle materials are liquids or solids such as mineral oil or aluminum oxide, respectively. The use



Figure 3 – Ground based outdoor experiment

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of these artificially introduced seeding particles is not feasible for flight tests and therefore a new approach must be determined. Actually, the best seeding for the in-flight PIV experiments is given by naturally-occurring particles in the atmosphere, such as in high-level cirrus clouds or low-level fog. Concerning the ground based measurements, stable soap bubbles give the best results due to their distinct seeding

behavior. At the moment several experiments have to be carried out to investigate the optimum implementation of these tracer particles.

The application of the PIV technique for large scale experiments promises to be a valuable approach for the visualization of complex wing vortex structures. The work done during the AIM program so far has already provided experience on laser safety issues and

favorable aircraft/airfield configurations of PIV systems. At the moment several seeding experiments are being carried out to determine the optimal implementation of the tracer particles. Nevertheless, there are still several challenges to deal with before this advanced experimental method has matured to a feasible level for "plug and play use".

Background Oriented Schlieren Method (BOS)

The future of high density visions

The Background Oriented Schlieren Technique (BOS) is an image-based measurement method for the visualization of density gradients. BOS provides information about the 2D displacement and has the potential to deconvolute the integrated information by applying density models or by using several cameras in parallel with different viewing angles. As little experience exists with the application of BOS in flight testing, ground tests with transport propeller aircraft and helicopters have to be performed to identify problems which need to be solved prior to the first flight tests.

Like other Schlieren methods, BOS is based on the deviation of light rays when propagating through a density gradient field. The quite simple experimental setup is shown in Figure 4. It consists of a camera focused onto a random pattern in the background of the density field under investigation. A point in the background plane is imaged by a bundle of light rays limited by the aperture of

the camera lenses (blue lines). A density gradient field placed between the camera and the dot pattern will cause a deviation of the light path (dashed lines), so

that the source point is imaged to a different position in the image plane than that obtained without this density gradient in the field of view.

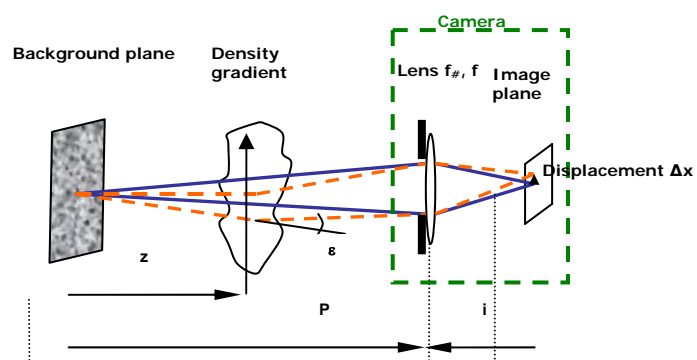


Figure 4 - Principle Sketch

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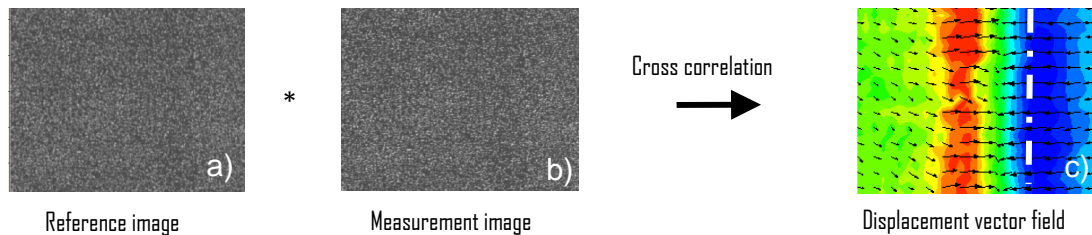


Figure 5 - Displacement vector field obtained by the cross correlation of the reference and the measurement image

The comparison of a reference image with no density gradient in the field of view with a measurement image with density gradient by using cross-correlation algorithms delivers the displacement vector field in the image plane. The example in Figure 5 shows the BOS measurement of a wing tip vortex in a wind tunnel. The vectors always point to regions of lower density, so in this case they are pointing to the vortex axis.

The final displacement in the image plane results from the integration of the

differential displacements along the complete light path. Thus the calculation of the density from the integrated displacements as seen by a single camera is only possible for the special cases of 2D- or axis-symmetric density fields.

The simple optical setup of BOS makes this technique interesting for in-flight applications. Nevertheless the special conditions mandated by the large scale and the in-flight restrictions like the optical access require special solutions. The main tasks to solve are to find an

appropriate background and the optimal camera position depending on the investigated object.

BOS has already been applied to investigate the compressible blade tip vortices (BTV) on the rotary wing of a helicopter. For the first measurements the helicopter was kept on the ground or performed a low hover flight. The cameras were installed on a nearby building so the ground could be used as the background plane. For the measurement shown in Figure 6 the additional speckles were applied with

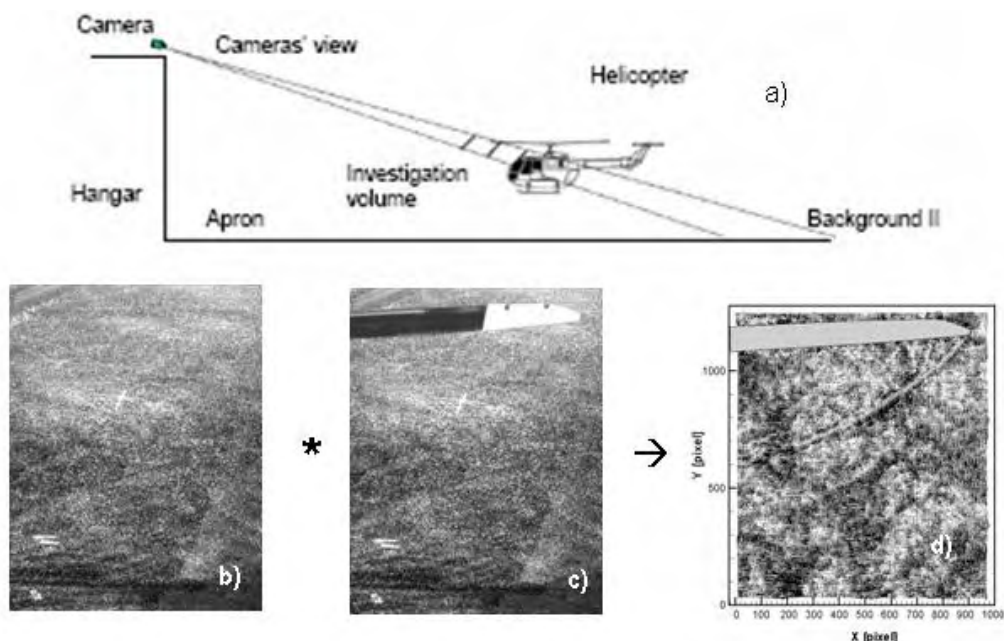


Figure 6a) BOS setup of blade tip vortex measurement on helicopter Bo 105

b) reference image

c) measurement image

d) BOS results: displacement vector field shows the structure of BTV

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white paint on the asphalt surface. In the displacement vector field the path of the BTV can be seen clearly.

In further tests the applicability of several natural backgrounds, such as grass, forests and the outskirts of the forest, was tested. Though the signal-to-noise ratio of the tested natural backgrounds is reduced compared to synthetic patterns, it is still sufficient for a BOS measurement. In conclusion the imaging of grass or small and dense leaves is preferable, leading to more homogeneous and reliable correlation data.

A further application for BOS in flight testing is the visualization of BTV of

propellers of fixed wing aircraft. Figure 7 shows an image of the Transall with running propellers. In this image the core of the BTV is visible because the lower pressure in the vortex core leads to a condensation of water vapor when the air temperature is close to the dew point. The density decrease accompanying the low-pressure had already been investigated successfully by means of BOS in a wind tunnel application (Figure 8).

BOS has a quite simple setup compared with other optical density measurement techniques like conventional Schlieren methods or interferometry, which makes it interesting for in-flight applications. The feasibility of BOS for

the investigation of BTV on helicopters has already been successfully demonstrated in several tests. A main challenge of this application is to find an appropriate natural background.

In an analogous way, the application of BOS for the visualization of propeller BTV seems to be feasible. Even if no ground or flight tests have been performed yet, the task is similar to the BTV investigations on the helicopter, and the small scaled wind tunnel measurements performed so far are very promising. The small dimension and near axial symmetry of the vortices facilitates the analysis of the BOS results.



Figure 7 - Propeller blade tip vortices visualised by condensation of the water vapour in the air

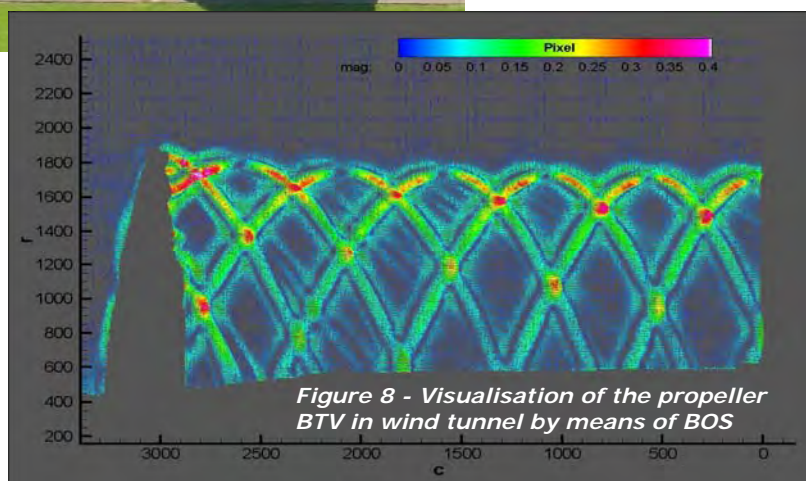


Figure 8 - Visualisation of the propeller BTV in wind tunnel by means of BOS

Image Pattern Correlation Technique (IPCT)

That's the point-of-view

During the certification process of a new aircraft the loads and thus the deformations occurring in free flight have to be measured to prove the safety of the structure. Strain gauges and accelerometers are commonly applied to measure the deformation and the movements of the structure. The installation of these sensors and their wiring, however, is very time consuming and often leads to substantial modifications of the aircraft structure. To minimize this effort, DLR and NLR developed advanced optical measurement techniques based on the Image Pattern Correlation Technique for in-flight experiments.

The Image Pattern Correlation Technique (IPCT) is based on photogrammetry in combination with modern correlation algorithms developed for Particle Image Velocimetry (PIV). The simplest IPCT setup consists of one monochrome camera observing the investigated object which is coated with a random pattern. After a reference image of a load-free object has been acquired (Figure 11a), the object is placed under a load which causes a certain deformation. The second image (Figure 11b) or a sequence of images is then recorded under such deformed states. The image(s) of the deformed object are then cross-correlated with the

reference image. A 2D displacement vector field (Figure 11c) is thus obtained as the result. Using image pairs of the randomly patterned object acquired by a stereoscopic camera system, its 3D position and shape can be obtained.

The basic principle of this stereoscopic IPCT, as employed by DLR, can be best explained by referring to its similarity to spatial vision in humans. Objects in the field of view are simultaneously observed under two different viewing angles. Similar patterns in both images are detected. If the viewing positions and the mapping functions of both optical systems are known, the 3D coordinates

of similar patterns identified in both images can be calculated by means of triangulation.

The NLR on the other hand, utilizes a single camera setup to record an area of the wing tip where a foil with irregularly distributed rectangles (to measure the local deformation) and four large markers (to register the coarse deformation) had been taped. Four of these single cameras are then used to measure under different viewing conditions. By using an analytical wing deflection model, the deformation of the wing could be described in terms of wing heave, torsion, twist and chord-wise curvature.

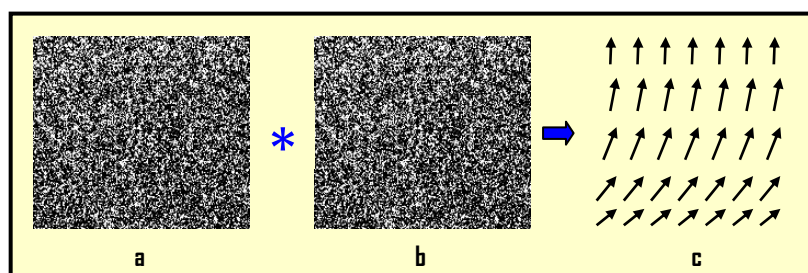


Figure 11 - Principle of the IPCT
a) reference image b) deformed image
c) displacement vectors

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Within the AIM project the capabilities of IPCT to measure both static and dynamic deformation of a wing on the ground and in flight are to be demonstrated. Therefore two different experimental setups have been designed and tested: one stereoscopic IPCT (designed by DLR in cooperation with Piaggio) and an IPCT approach based on a deflection model (established by NLR).

With the first setup two measurement tasks can be performed: a generic ground vibration test and the in-flight deformation measurement. The first stereoscopic IPCT test performed on the Piaggio P 180 was the generic ground vibration test carried out in November 2007.

In Figure 12 the principle of the setup for the measurement is shown. Two cameras installed on

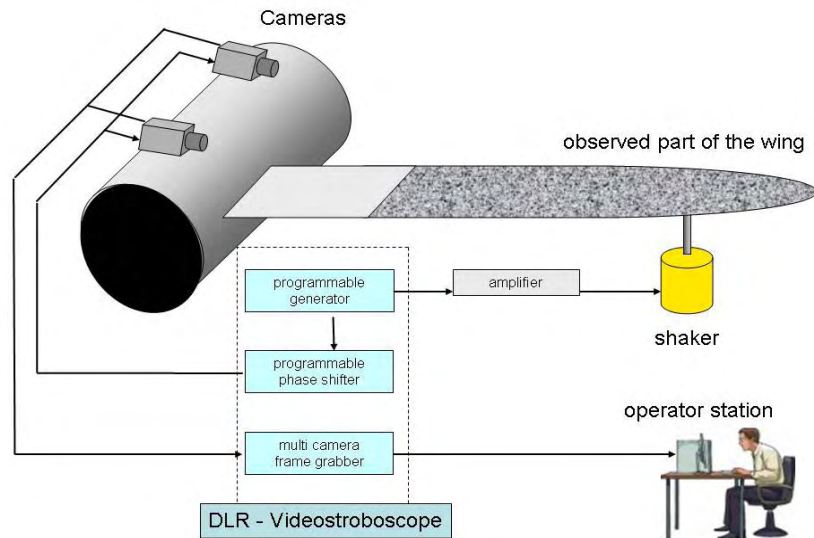


Figure 12 - The experimental setup for the ground vibration test using stereoscopic IPCT

top of the fuselage recorded images of the outer part of the excited wing. A foil with a printed random dot pattern was affixed onto the upper wing surface. The excitation of the wing was performed by an electromagnetic shaker. The excitation signal was produced by a programmable generator integrated in the DLR Videostroboscope system. The exciter signal

was fed also into the integrated phase shifter which time stamped the recording of the camera images. To record the images at specified phase angles of the oscillation a desired frequency was set and the recording of the images was carried out while shifting the phase step-by-step from one oscillation to the next. After having recorded the images

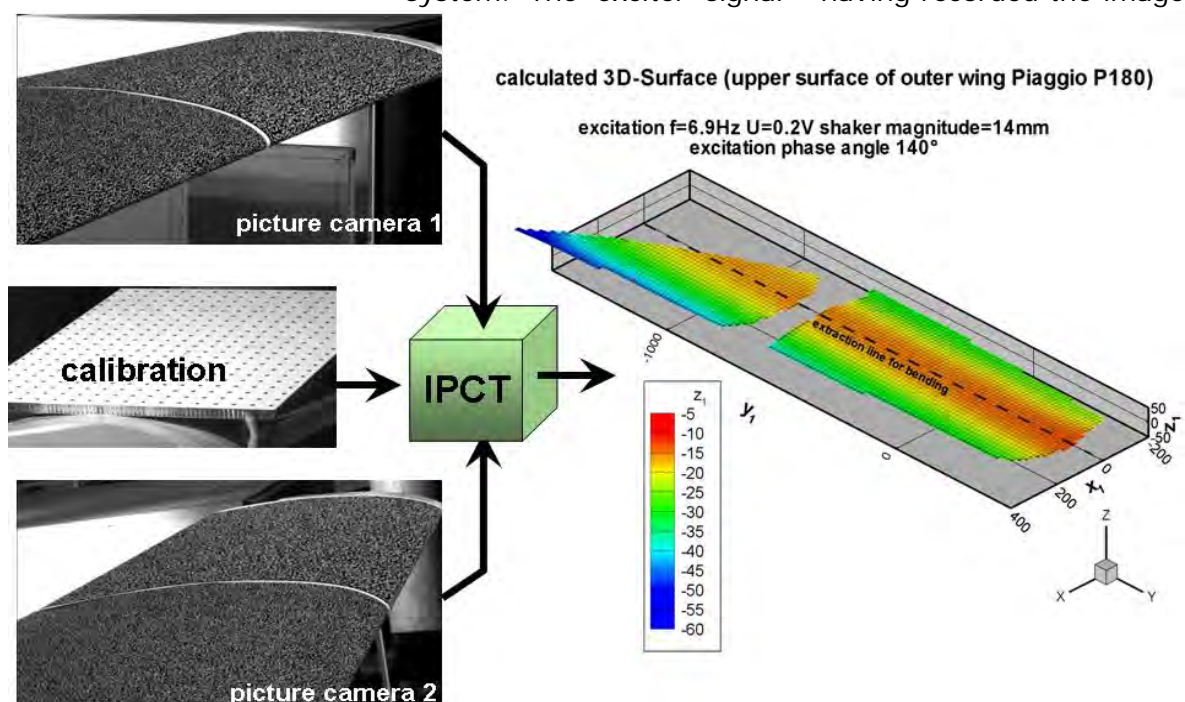


Figure 13a - Recorded images and measurement result

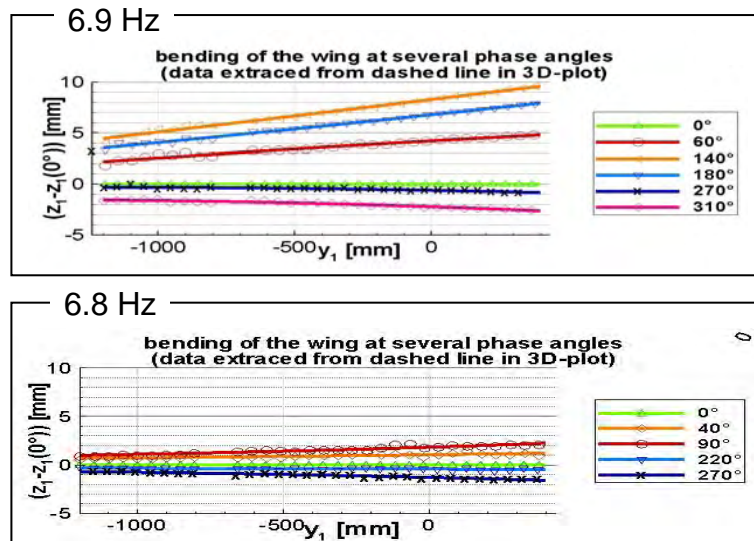
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at all required phase angles the next frequency was set.

Due to the small height of the fuselage above the wing, the viewing angle between the cameras line-of-sight and the outer wing surface was very small. With cameras mounted on top of the fuselage only about 6° could be attained; however, for an optimal IPCT setup about 30° should be chosen.

In Figure 13a a sample pair of recorded images and the 3D surface of the outer wing calculated from these pictures are shown. The displacement of the wing with respect to the reference state (wing at rest) was extracted along a line in spanwise direction. By comparing the maximum and the minimum deflection the amplitude of the wing at the structural response to the invest-

Figure 13b - Bending curve for each excitation phase angle

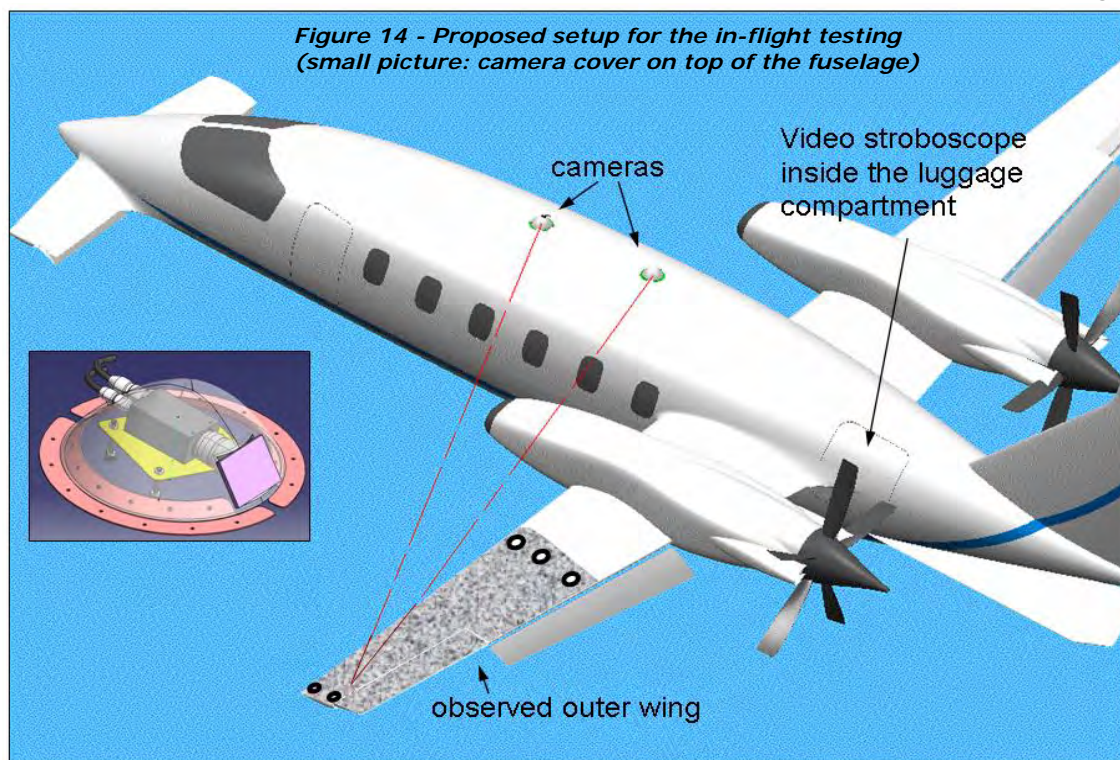


igated excitation frequency and the phase lag can be identified. Figure 13b shows that at 6.9 Hz the amplitude was about 14 mm which could be confirmed by a calliper measurement. The phase lag was around 90 degrees, which is an indication for the occurrence of a resonance.

By extracting the amplitudes at the same position on the surface at different excitation frequencies a spectrum with the eigen-frequencies can be obtained.

For the generic ground vibration test a shaker synchronized with the imaging system had been used to excite the wing in a

Figure 14 - Proposed setup for the in-flight testing
(small picture: camera cover on top of the fuselage)



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harmonic way. This configuration can not be used for the planned optical in-flight deformation measurements, however, where a transient wing excitation will occur. Therefore the cameras should run synchronized to each other with a frame rate high enough to capture faithfully all excited frequencies of the wing. All recorded images will be tagged by a GPS synchronized time which enables their synchronization with the flight parameters of the aircraft. Besides these data recording challenges, an installation suitable for flight testing had also to be designed.

The setup chosen by DLR and Piaggio Aero Industries can be seen in Figure 14. The cameras are fixed onto the main beam of the fuselage and protected by an aerodynamic cover. To correct for unwanted camera movements, the recalibration algorithm of the LaVision post processing software package will be used. Therefore a few dedicated markers on the wing are needed. The random dot pattern will either be adhered to or sprayed onto the surface. The video stroboscope will be located in the luggage compartment of the P 180.

In AIM Work Package 1, wing deflection measurements on the NLR Fairchild Metro II were performed using also the Image Pattern Correlation Technique (IPCT) based on a wing deflection model. NLR equipped the aircraft with

Figure 15 - Fairchild Metro's wing partly covered with speckles to enable IPCT measurements.



four cameras – two state-of-the-art cameras installed in the cabin and two miniature cameras on top of the fuselage. The cameras recorded an area of the wing tip where a foil with irregularly distributed rectangles (to measure the local deformation) and four large markers (to register the coarse deformation) had been taped. The NLR used these four single cameras to check different viewing conditions. By using a wing deflection model, the deformation of the wing could be described in terms of wing heave, torsion, twist and chord-wise curvature. Using this setup, NLR carried out a ground test in the hangar to assess and improve the accuracy of the installation. On-ground comparison of IPCT results with micrometer measurements demonstrated submillimeter accuracy of this technique. After this pre-test, NLR performed a successful flight test campaign with a Fairchild Metro II. During three flights in the period August 22 – 24 2007, large amounts of good quality

measurement data were recorded.

After post-processing and analysis of the measurement data a wealth of interesting results was obtained. Planar deformation of the wing area as a function of wing load could be accurately described in terms of wing heave, torsion, twist and chord wise curvature, while in addition interesting local behavior of the wing was observed: at the main spar a reduced displacement was observed, as expected, while a wing area was discovered showing buckling behavior (just of the order of 0.4 mm deflections). Architectural schemes of the wing construction showed reduced local wing support here in terms of ribs and spars for the support of the plates.

In addition to these static measurements, observations of wing dynamics were performed using IPCT. Two eigenfrequencies at 4.54 Hz and 7.88 Hz were measured. Also wing dynamics during aircraft landing and taxiing could be studied.

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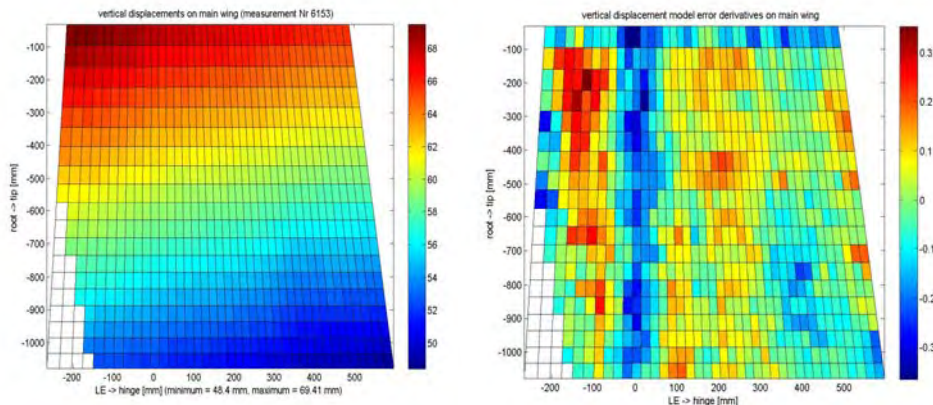


Figure 16 L - Vertical displacements of wing surface during 2g normal load conditions

Figure 16 R - Correlation of displacement local behavior with normal load. Displacements at 0-cord line are reduced as the wing's main spar is integrated at the 0-cord line

These dynamic IPCT measurements proved to be in excellent agreement with simultaneously performed accelerometer measurements, where a three axes-of-freedom accelerometer mounted at the end of the main spar had been used. In addition to the main wing, in-flight aileron deflection has also been characterized using IPCT: the aileron heave, aileron rotation about the hinges and the changes of the aileron gap to the main wing's trailing edge have all been determined. The IPCT-measured aileron rotation agreed with results measured with a synchrometer to an accuracy of better than 0.15° . The (small) measurement discrepancy is thought to come from the in situ synchrometer calibration being performed in the hangar at 20°C , while the in-flight measurements took place at approximately 0°C .

The presented ground and flight tests demonstrated the good performance of the measurement system and the robustness of IPCT. The obtained preliminary results give a preview to the potential of stereos-

copic IPCT to measuring planar deformations non-intrusively with a high accuracy within a short time. Concerning the Piaggio flight test campaign further development of the measuring system and the measurement technique was carried out; for example, the implementation of an integrated GPS module into the video stroboscope to enable a precise synchronization of the IPCT measurements with other data recorded during the flight test. Also the capability of measuring the structural response to transient excitations was improved by recording camera images at higher frame rates. Another big issue for the application of IPCT for cost effective flight testing is the development of procedures to apply the dot pattern to the surface in a fast and reversible way. At the moment adhesive foil or sprayed permanent color are used. This may be not suitable if large areas have to be covered by the pattern. Small single stickers or chalk spray are conceivable solutions.

The improvement of the algorithms for identification

and correction of unwanted camera movements as well as the modification of the calibration procedures towards large scale applications are tasks for the future.

Nevertheless, modern optical measurement techniques such as stereoscopic IPCT become more and more interesting for advanced in-flight testing and will complement conventional measurement techniques in the near future to make industrial flight testing more efficient, thus enabling time and cost reductions. In general, the IPCT technique has been proven to be applicable for in-flight investigations. Measurements of the propeller or rotor blade deformation and wing deflection are feasible.



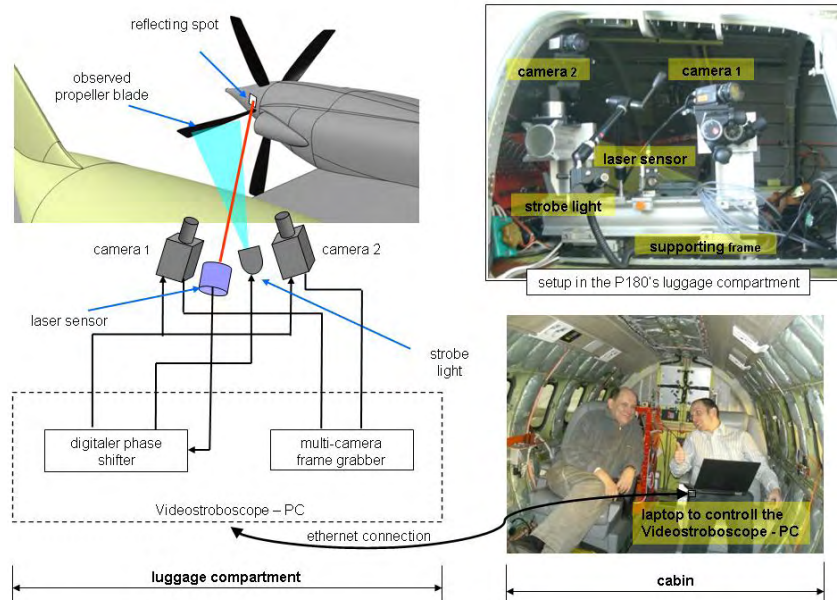
Quantitative Visualization Technique (QVT)

The trigger for an advanced visualization technique

The qualitative visualization of flows and moving objects has been improved considerably by the development of CCD sensors with high temporal and spatial resolution. Due to the processing power of modern computers, the image data can also be rapidly analyzed to yield quantitative information about location, geometry, intensity etc. and the structure of such objects. At DLR a special multi-camera video system has been developed for various applications of quantitative visualization. The cameras of this system work in non-standard video mode, i.e. their shuttering and triggering are freely programmable, and they can be synchronized with external events. The QVT system has been applied to a number of industrial tests in aerodynamics, turbo machinery and medical applications and should now be in a position to find its way into extensive aerospace application.

A combination of high-speed stroboscopic imaging with the Image Pattern Correlation Technique (IPCT) enables non-intrusive measurement of surface deformation of fast vibrating or rotating objects. The in-flight investigation of the deformation of a fast spinning propeller is a demanding task. It is obvious, that conventional methods like strain gauges and accelerometers are difficult to use because of problems with their installation, their wiring, the data transmission, and the balancing of the propeller. Furthermore such sensors provide their data only at the location where they have been installed. Within the scope of the AIM project another very interesting measurement task, which is performed on the P 180, is the optical measurement of

Figure 17 - Setup used for the optical propeller deformation measurements on the P180



the deformation of propeller blades at different flight conditions.

In contrast to the wing deformation measurements, where the investigated object is continuously in the line-of-

sight of the cameras, the propeller blade periodically passes the cameras' field-of-view only for a short time and at a high speed. Therefore the camera recording has to be synchronized very accurately with the rotation

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of the propeller. Figure 17 gives an overview of the setup used for this kind of stereoscopic IPCT measurement on the P 180. Two HS/JAI CV-A1 cameras with a resolution of 1392 by 1040 pixels and the Videostroboscope-PC are installed in the luggage compartment of the aircraft. Windows in the compartment door enable a free sight to the passing propeller blade. A selected blade is painted with a dot pattern to measure its deformation.

In addition some markers are affixed on its surface for the needed recalibration algorithm as well as for fast position detection. The recording system has to be synchronized with the rotation of the propeller. This is realized by using a laser sensor pointing onto a reflecting pad on the propeller spinner. Every time the reflector passes the laser beam, the device

sends a TTL pulse to the phase shifter of the Videostroboscope-PC which calculates the rotation frequency from this signal and triggers the cameras at a desired phase angle. As the phase shift does not depend on the signal frequency the selected blade will be imaged in the same position at each propeller speed. To avoid motion blur due to the high rotation speed of the propeller, the shutter time of the cameras has to be very short (5 μ s to 50 μ s). To expose the images with enough light a high energy strobe illumination has to be synchronized with the cameras.

To test for proper triggering, a ground test with running propeller (and thus the highest vibration level) had been performed in November 2007.

In Figure 18 some results of this test are shown. It

can be seen that the images taken during the ground run provide satisfactory quality for IPCT evaluation. They are well exposed and no motion blur can be observed. During the test the propeller speed was increased from 1000 rpm to 2000 rpm. The triggering and phase-shifting worked so well that despite the varying speed the position of the image of the passing blade on the frame was stable. Due to the phase-locked recording, changes of the angle-of-attack of the blades could be observed easily, as well as the deformation of the blade itself.

Applying QVT to larger scales is not only a function of the magnification factor. Additionally the accuracy of the measurement technique has to be adapted to capture images of moving objects at defined times. Using these images for an IPCT measurement, for

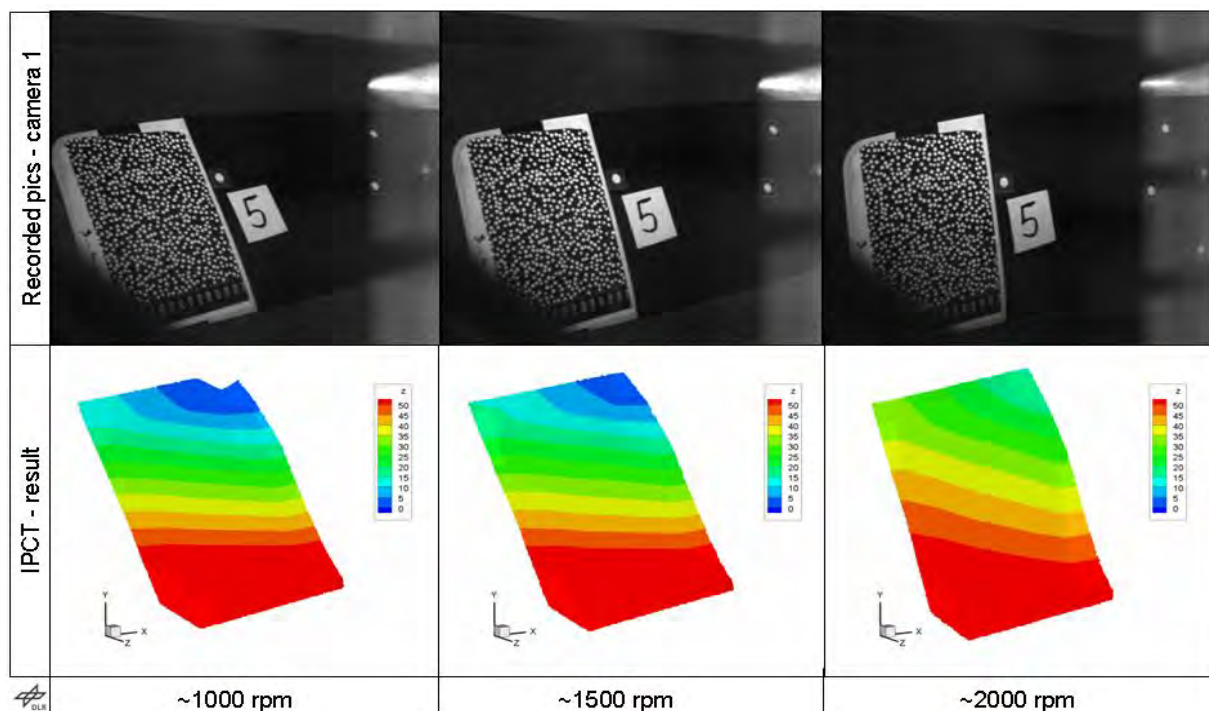


Figure 18: A blade recorded at 1000, 1500 and 2000 rpm. Below: corresponding IPCT results

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example, the deformation of a surface can be determined. QVT enables imaging of periodic incidents with high repeatability and high time

resolution. The outputs of the system are images of different object conditions. For example, to quantify the deformation of a propeller blade, IPCT is

needed to compare the images and to get accurate data concerning the local deformations.

Light Detection and Ranging Method (LiDaR)

Capturing the invisible knowledge

On the basis of recent developments, fibre LiDaR technology becomes a serious candidate for lightweight, compact, eye-safe airborne anemometer probes. The contribution of the ONERA to this technology is the design of a $1.5\ \mu\text{m}$ LiDaR sensor which is able to detect the tip vortex. The experiments took place during a ground-based test campaign of the DLR helicopter in hover flight in ground effect conditions. The main outcome of this work is the specification of a future $1.5\ \mu\text{m}$ LiDaR anemometer for onboard research and industrial tests.

In general, LiDaR (Light Detection and Ranging) is an optical remote measurement technology that determines the precise properties of scattered light to obtain important information of a distant target. This procedure is based on a Doppler shift measurement of a light wave obtained from a single frequency laser that is reflected from naturally occurring atmospheric aerosols (Mie scattering).

The frequency shift of the reflected wave is proportional to the air velocity component in the viewing direction and is detected via an interferometer which measures the beat frequency resulting from the interference between the back-scattered wave from aerosols and a reference wave (local oscillator). Coherent mixing enables recovery of the backscattered wave phase. This phase contains the

radial velocity information (along the laser line of sight). If required, the true air speed in three dimensions can be derived from multi-axis sensing either with the help of at least 3 beams, or with a scanning device. LiDaR is able to determine the velocity with no in-flight calibration and no distortion.

In 2007, the work of the ONERA led to the specification of the $1.5\ \mu\text{m}$ LiDaR sensor and was aimed at a simulation of the $1.5\ \mu\text{m}$ LiDaR performance. The year 2008 was devoted to the $1.5\ \mu\text{m}$ LiDaR sensor implementation, LiDaR measurements tests on a DLR helicopter in hover flight and their evaluation.



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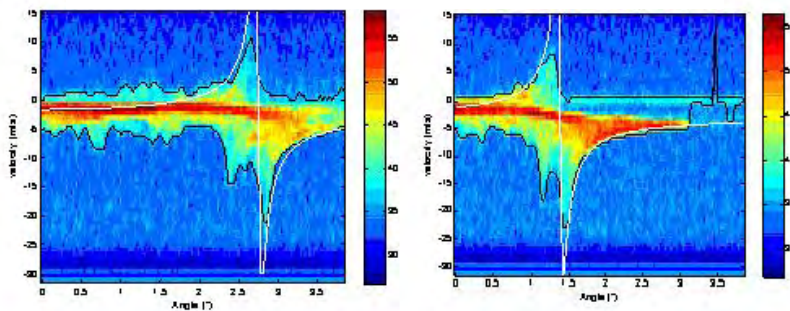


Figure 20 – Vortex velocity LiDaR images in 10° plane observation without helicopter thrust

Outdoor ground-based LiDaR measurements have been performed on DLR's MBB 105 helicopter in hover flight above ground.

Figure 19 illustrates the LiDaR installation at the site of the trials at Braunschweig DLR airport.

LiDaR tests require tracer particles to increase measurement sensitivity and therefore to improve the quality of the wind field imaging. During the LiDaR tests, a seeding device with smoke particles was used. It was shown that the seeding of these particles was very difficult, so that a high and uniform seeding density in the region of interest could not be obtained. This system was less efficient than the initially planned oil seeding, which uses an air compressor to inject the

tracer particles into the vortex flow. A changed collective pitch and rotor thrust setting during the experiment caused strong distortions of the seeding distribution within the observation zone. This is the reason why the LiDaR measurements were performed most of the time with the helicopter running without rotor thrust.

However, the field tests provided interesting results. LiDaR tests were carried out for two days with 6 hours of helicopter time. Measurements were made at different vortex ages corresponding to the observation planes of 10°, 40° and 70° behind the trailing edge of the blade. The experiments were carried out with a velocity accuracy of 1 m/s and a velocity dynamic of ± 40 m/s.

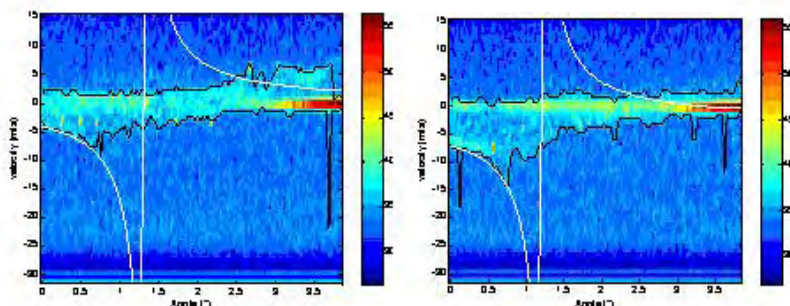


Figure 22 - Comparison between LiDaR measurements and PIV vortex model with helicopter thrust

The Figures 20-22 illustrate several LiDaR images of the vortex velocity field in 10° plane observation for 3.8° LiDaR scanning angle and without helicopter thrust.

The obtained results indicated a maximum vortex speed of 15 m/s and -25 m/s with an angular distance between these two speeds of about 0.25°. A wind field or vortex close to the blade tip vortex was also captured and measured by the LiDaR sensor.

Doppler LiDaR measures the tangential velocity of the blade vortex. One way to characterize a vortex is by defining its velocity profile. The LiDaR velocity

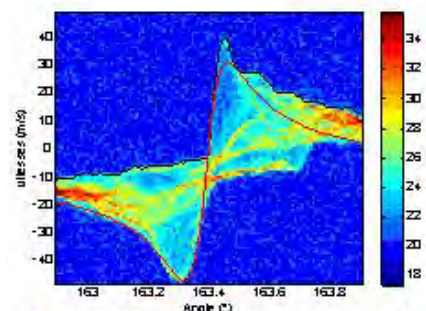


Figure 21- LiDaR measurement simulation using vortex velocity data measured during PIV tests

image can be converted to a radial vortex field distribution (or 2D vortex velocity) according to a vortex model. Previous LiDaR wake vortex measurements had demonstrated that the so called Hallock Burnham vortex model provides the best fit for the conducted LiDaR experiments. Model parameters were adapted to the measured rotor wind field. These adjustments are the same for all LiDaR images: in Figure 20, vortex model

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(white curve) fits vortex LiDaR measurements for circulation parameter: $\Gamma_0 = 2.8 \text{ m}^2/\text{s}$ and for maximal speed: $v_{\theta\text{max}} = 29 \text{ m/s}$.

To compare LiDaR results with given PIV data, several simulations of LiDaR measurement have been carried out using vortex velocity data measured during PIV tests. The velocity field provided by DLR had been determined on a Bo 105 for 2T thrust at a vortex observation plane of 3° behind the blade and for 1° of field of view. Figure 21 shows a vortex field of small dimension with an angular spreading of 1° and a maximum speed of -45 m/s . The angular size of the vortex core is about 0.15°

(distance between 2 speed maxima). PIV measurements are fitted by the vortex model (red curve) on Figure 21. A good fit is obtained for circulation parameter: $\Gamma_0 = 6 \text{ m}^2/\text{s}$ and for maximal speed: $v_{\theta\text{max}} = 39 \text{ m/s}$. We also observe that the blade vortex is disturbed by another wind field.

During the LiDaR tests some recordings led to incomplete LiDaR images due to the fact that the image did not show the whole vortex. An applied fit with a PIV based vortex model using the slope of velocity given by LiDaR is able to provide the missing information. Figure 22 compares the PIV vortex model (white curve) with LiDaR measurements. Good

agreement has been obtained between the LiDaR fit and the PIV fit using the same vortex model parameters (circulation parameter: $\Gamma_0 = 6 \text{ m}^2/\text{s}$ and maximal speed: $v_{\theta\text{max}} = 39 \text{ m/s}$).

To conclude, even with imperfect seeding, experimental results of the LiDaR tests prove the capability of the LiDaR technique to detect helicopter blade tip vortices. Blade tip vortex velocities of a hovering helicopter were measured by a $1.5 \mu\text{m}$ LiDaR sensor with very good speed accuracy (1 m/s) and characterized in terms of circulation using the Hallock-Burnham vortex model.

Pressure Sensitive Paint (PSP)

Investigating under pressure

For in-flight testing it is hard to obtain pressure distributions on wing surfaces at high spatial resolution due to the limitation of the maximum number of pressure taps which can be installed in the available space on the wing. As the position of the pressure taps cannot be changed after manufacturing, major problems can occur if the expected aerodynamic phenomenon to be investigated does not appear at the expected locations on the model surface. In contrast, the PSP method enables the measurement of planar pressure distributions over the visible surface of the aircraft/model. It provides maximum flexibility for any given measurement situation.

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In order to utilize PSP, the model must be coated with a Pressure-Sensitive Paint. In such paints a photochemical process takes place where the luminescent coating absorbs energy of the incident light (UV or visible light) and emits light at longer wavelengths. When this luminescence is quenched by oxygen, an increase of the local pressure (associated with an increase of local oxygen concentration) decreases the intensity of the coating's luminescence. The relationship between this intensity and the pressure is given by the Stern-Volmer Law, and this constitutes the fundamental of the PSP technique. In short: the brightness of the luminescence of this paint under special illumination is a measure of the local pressure.

Pressure-Sensitive Paint (PSP) is widely used nowadays to measure pressure distributions on a

model in a wind tunnel. In applying PSP to flight testing, there are problems such as suitable illumination, influence of atmosphere during flight test, icing and temperature correction that need to be tackled. The biggest problem is the large distance between the detecting CCD-camera and the region of interest (ROI) on a wing where the PSP has been painted. This large distance leads to low signals for a PSP measurement in flight testing. Also one must pay attention to

limited space and the conditions of flight testing. There are thus different requirements for flight and wind tunnel testing which need to be addressed here.

The first PSP in-flight measurement within the AIM project was performed using the ATTAS aircraft (Figure 23) in October 2008 in Braunschweig/Germany to check the feasibility of PSP in flight tests. Figure 24 shows the experimental setup of the PSP- and IRT-systems used in this test.

Figure 23 – ATTAS experimental aircraft

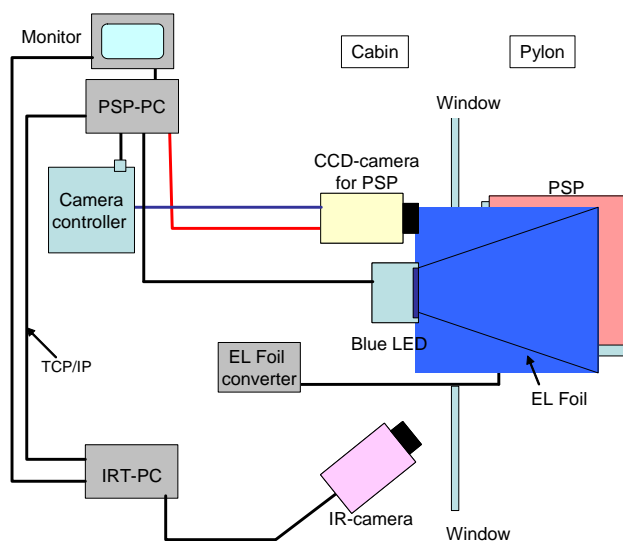


Figure 24 - Schematic view of experimental setup

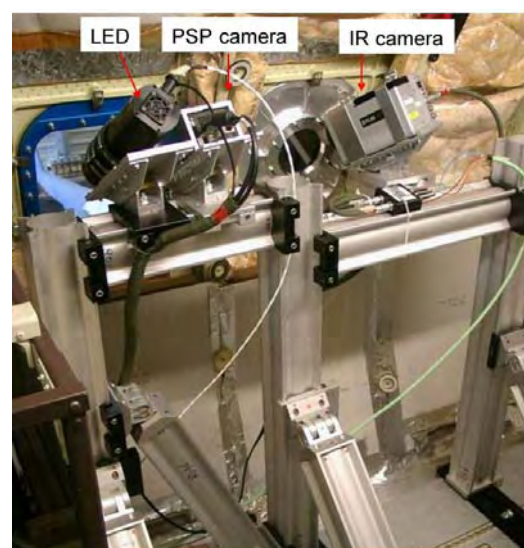


Figure 25 - Camera and light source setup

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PSP, which was applied to the pylon as shown in Figure 26, was illuminated by an LED-array from an observation window (Figure 25) or an Electro-Luminescence (EL) foil placed underneath the PSP layer (Figure 26). The distance between the cameras and the coated surface was about 2 m. The emitted light from the PSP was observed by a CCD camera which was installed at the observation window. The temperature distribution on the PSP layer was observed by the IR camera to correct the influence of temperature on the PSP results. One pressure sensor was installed within the region of interest for purpose of comparison with PSP results, as shown in Figure 26.

A preliminary result obtained using the LED-array as a light source is shown in Figure 27, where flight conditions were $Ma=0.56$, height of 21000 ft and static air temperature of $-24\text{ }^{\circ}\text{C}$. The temperature correction of the PSP result



Figure 26 - PSP and EL-foil on the pylon

was made using just one central value of the temperature for each reference and run image.

The pressure distribution on the pylon is clearly shown in this figure. Figure 28 presents the cross-sectional pressure distribution along the A-A', B-B' and C-C' sections in Figure 27.

One can see the high pressure region at 0.55 of the line A-A', which is also shown in Figure 28 as a white region. The pressure sensor exhibits an offset value of 5 kPa in comparison to B-B' and C-C' which are located near the sensor. This error is

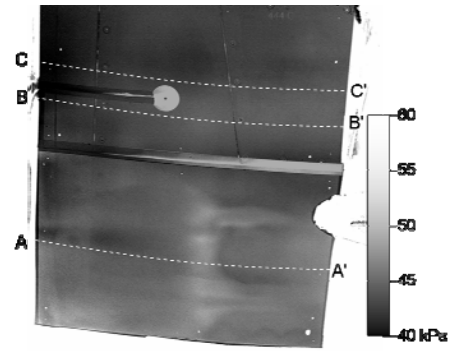


Figure 27 - Pressure distribution at $Ma=0.56$

probably due to the temperature dependency of the PSP. More accurate values are expected by careful temperature correction using the IR data.

This result from the first flight test proved the feasibility of PSP even under flight-test conditions. Thus the PSP technique can become an excellent tool for the investigation of aerodynamic phenomena on complex 3D models. The influence of vortex interactions on the pressure map on the surface of the model can be clearly analyzed using PSP. The pressure data can be obtained in near real time.

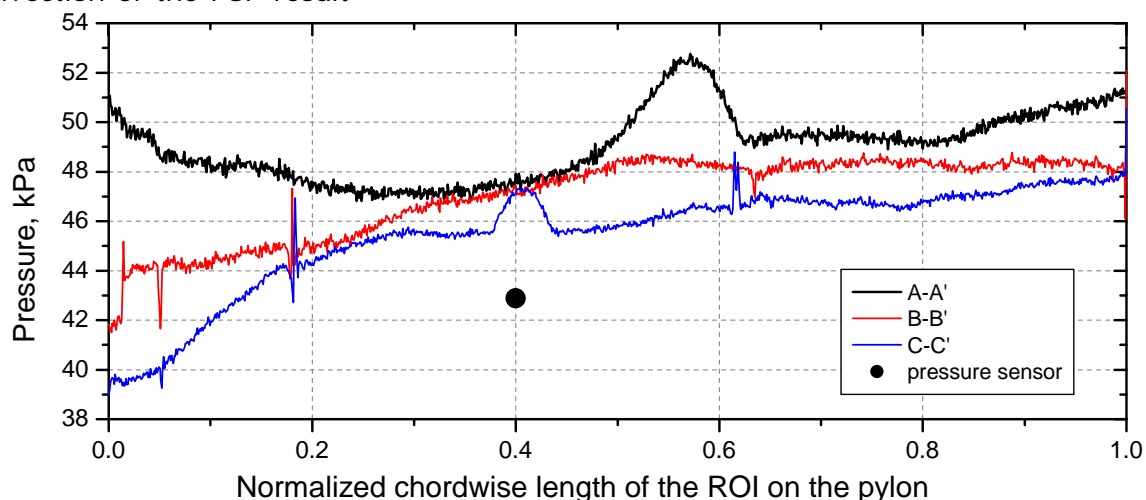


Figure 28 - Cross-sectional pressure distribution along A-A', B-B' and C-C' in Figure 27

Infrared Technique (IRT)

Finding the hot spot

The Infrared Thermography Technique is based on the measurement of the infrared radiation from surfaces and enables a global determination and visualization of the surface temperature distribution with high accuracy. The main objective of the application of the infrared technique within the AIM project is the determination of the surface temperature of helicopter (non-) rotating parts and the visualization of engine exhaust gas flow.

The electromagnetic spectrum is divided into different wavelength bands. The infrared band covers wavelengths ranging between the boundary of the visible light ($0.7\ \mu\text{m}$) and the microwave limit ($1000\ \mu\text{m}$). An IR camera can in particular measure and image the emitted infrared radiation coming from a hot object. The fact that the spectral distribution of this radiation depends on the object surface temperature makes it possible for the camera to measure its surface temperature. These spectral distributions are defined by Planck's Law and Wien's Displacement Law (decreasing of the main wavelength as the temperature increases). It is further known that the total power emitted in a given IR wavelength band is proportional to the 4th power of the absolute temperature of the object (Stefan-Boltzmann's law). It is this correlation which is used in the IR measurement technique to derive object temperature.

It is important to note that while thermal imaging displays the amount of infrared energy emitted by an object, it is quite difficult to get an accurate temperature reading of a specific subject using this method. The energy displayed in a thermal image represents three types of energy: emitted energy, atmosphere energy and reflected energy. The energy received is the sum of all these three radiation energy sources.

The atmospheric energy is the energy emitted and

transmitted through the atmosphere, the lens and up to the infrared detector. It depends on the atmospheric temperature and the transmittance of the atmosphere. The emitted energy is the energy radiated by the object (Planck's law) and transmitted through the atmosphere and the lens up to the infrared detector. This type of energy can be derived with the help of the Stefan-Boltzmann law (emitted energy proportional to T^4), the emissivity of the object and the transmittance of the atmosphere and

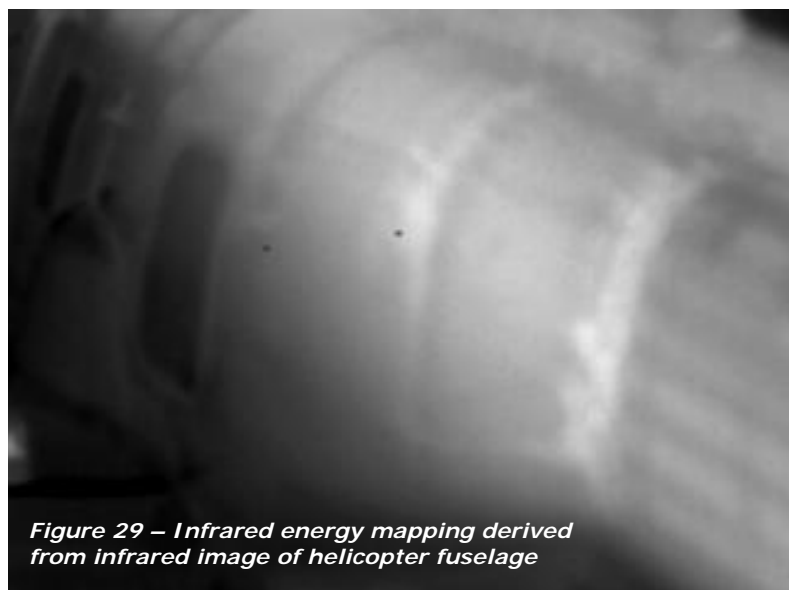


Figure 29 – Infrared energy mapping derived from infrared image of helicopter fuselage

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eventually of the optical lens. The reflected energy is the energy of external source radiated by the object and transmitted through the atmosphere and the lens to the infrared detector. This kind of energy depends on the temperature of the external source, the emissivity of the object and the transmittance of the atmosphere. In the long run, to derive the surface temperature from the infrared image, all these parameters have to be determined.

By finally knowing the temperature distribution on a surface, different conclusions can be reached. Very often the temperature itself is the desired value. This is the case e.g. for measurements concerning the temperature of the airframe. EC-F is already carrying out such measurements, especially around the exhaust of the turbines where the temperature is of high interest assessing the stresses on the airframe (Figure 29 and 30). Since the IRT was already successfully used for investigations on fixed wing aircraft

(as was done by DLR did in Braunschweig), the application in this case is of low risk. However, there is still a major difference between the known applications and the helicopter experiments because a direct view of the investigated surface is limited. Strong density gradients due to the passing blade tip vortices and the exhaust plume in front of the surface will have an impact on the spatial accuracy of the measurement. This problem must be solved or its influence estimated.

Another application of IRT involves deriving flow field information from the surface temperature distribution. In aerodynamic research (in wind tunnel and flight tests) thermography is primarily used for the investigation of boundary layers.

To integrate such a system into the flight test environment, the whole assembly should be able to withstand strong vibrations of a high frequency range, high temperatures and a polluted gas flow. Therefore the best compromise bet-

ween camera on ground or installed on the helicopter has to be investigated as well as the use of removable controlled emissive paints. In addition, to prove the feasibility of this measurement technique, this method will have to be capable of determining the structural temperature with an absolute accuracy of about $\pm 5^\circ\text{C}$ and it should be easy to implement this technique in a flight environment.

To measure surface temperature, the infrared technique offers some clear advantages compared with traditional techniques (2D + non intrusive methods). No major problems are expected for the application of standard IRT for flight testing. Infrared technique seems to be today fully applicable to helicopter industrial flight testing but demonstration has to be performed in the flight environment (emissivity, reflection and transmission). The flight test proposed in the AIM framework concerns the measurement of the surface temperature of a helicopter structure heated by the engine exhaust gas flow. However, in order to be used in parallel with PSP (see page 19), the accuracy must be improved due to problems such as moving reflections (e.g. clouds, different thermal structures of landscape) during flight tests. This requires sophisticated procedures and algorithms for calibration, dewarping and the matching of images.

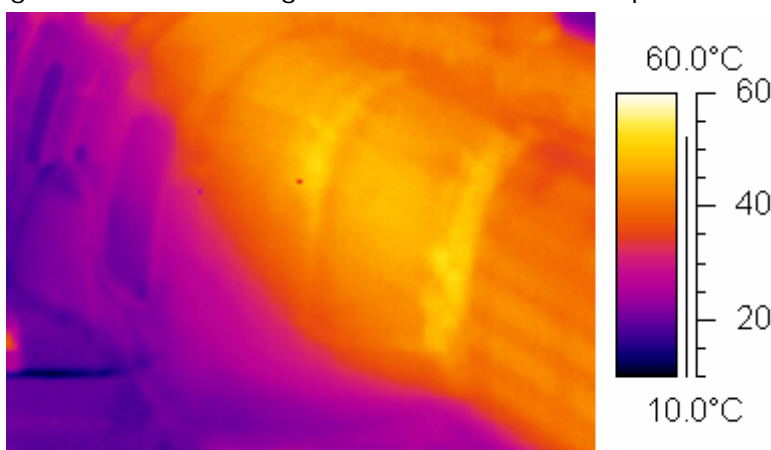


Figure 30 – Temperature mapping derived from the object infrared image

State of the Art

The following table presents an overview of the current state-of-the-art of each of the above mentioned techniques with respect to in-flight applications including the development and adaptation work planned within AIM to achieve the capability for in-flight testing. The dark blue fields indicate that the techniques are already in use and the light blue fields show the planned points of action within the AIM project.

Application		Laboratory	Wind Tunnel, Research	Wind Tunnel, Industrial	Ground Test	Flight Test, Feasibility	Flight Test, Operational
Technique	Page						
PIV	4					AIM	
BOS	6					AIM	
IPCT	9						AIM
QVT	14						AIM
LiDaR	16						AIM
PSP	18					AIM	
IRT	21						AIM

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Airbus A380



VW 614 ATTAS



Eurocopter EC 225



MBB Bo 105



Eurocopter EC 135 ACT/FHS



Dornier Do 228



Fairchild Metro II



Piaggio P 180 Avanti II

