Modern image-based experimental methods for application in fluid dynamics

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Abstract

Experimental methods for the investigation of complex flow phenomena have primarily been developed for applications to problems of industrial interest such as aerodynamics. Mostly point-wise methods to determine flow velocity, pressure, temperature, density, etc. have been utilized in the past. One disadvantage of these methods is that they require a probe to be inserted in the flow field, i.e. the flow phenomenon to be studied may be influenced by the presence of the probe. Due to the recent technological progress (lasers, optoelectronics, high resolution high-sensitive video sensors, processing speed and memory capacity of computers, development of advanced evaluation and post-processing algorithms) image-based measurement techniques have been developed which allow to observe flow phenomena from a large distance. These image-based methods have found application as standard and robust measurement techniques for aerodynamic investigations in industrial wind tunnels in the past decade. In parallel they are more and more often used for the investigation of flows in nature as well. An overview of the most important image-based measurement techniques as well as an assessment of their potential to be used for flows in nature will be given.

1 Introduction

The development of measurement techniques for flows is driven by the demands of industrial applications such as aerodynamics, turbomachinery, car industry, chemical industry, and so on. In general, these applications are performed in easily accessible free flows, sometimes the access is limited by walls. The investigations concern flow fields around models, which are stationary, sometimes moving or rotating. In a few cases the models are deforming as well. In most cases the start of an event to be investigated can be triggered externally: the movement of an object is mechanically driven and thus known a priori. Stationary or periodic flows allow the flow field to be scanned in space by a single probe in temporal sequence in order to compose the complete flow field after the measurement. In most applications transparent air or water flows are studied.

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Multi-phase flows are of interest in the chemical industry. Standard applications range from low speed (a few cm/s) to transonic flow regimes. Mostly, small-scale models of the real object of interest are investigated. The dimensions of the models and the observation areas range from a few centimetres to a metre. The measurement of full-scale objects (larger than a few metres) usually is not possible. In the past few years a strong development of measurement methods for flow fields with dimensions of less than a millimetre (micro- and nanotechnology) have taken place as well.

This brief description shows that the demands arising from the investigation of technical objects with respect to appropriate measurement techniques are limited, especially when comparing them to those arising from the investigation of flows in nature, which will be discussed next. From the point of view of technical flows, the greatest similarity to flows in nature will be found for those flows concerning ‘dead’ (i.e. non-living objects). One can think of flows in rivers and currents in oceans, avalanches or mudslides, clouds, vortical structures in the lee-side of mountains and islands, high- and low-pressure systems in the atmosphere, etc. The general features of the flows in ‘dead’ nature are that the object under inspection is observed directly. Thus, mostly flows of very large scale and rather low-flow velocity have to be studied. Usually these objects move in air and water, without constraints form external walls and are thus easily accessible by imaging methods. In contrast, the observation of flows around or even within living objects is much more complicated. In general, such objects move and deform. For animals/humans their movement does not just follow the laws of fluid mechanics passively but can be influenced by external stimuli or deliberately in case of higher order species. In such a case the ‘activity’ of a living object needs to be taken into account as well for predicting its movement. The laboratory environment, the measurement probe by its geometry or the measurement technique (tracer particles, laser light, dyes for flow visualization, etc.) are stimuli which in most cases will influence the behaviour of the living object. Moreover, it is difficult to achieve reproducibility and statistical information (reliable data averaged over many experiments and different realizations of the same object). In order to be able to deal with these problems, models of the living object (e.g. of a bird, fish or blood vessel) have been studied. If proceeding in such a way the complexity of the measurement task can be reduced to that known from the application of measurement techniques in technical flows. As a side remark one should say that the increased complexity of living objects as compared to technical objects is of course a consequence of the much different time scale of the evolution/development of such objects. However, as technical objects also require increasing complexity to fulfil the demands of today’s designers, it becomes common practice in engineering to try to learn from the design developed in nature by evolution. Consequently, measurement techniques needed for technical objects will have to reach the same level of complexity as required for living objects in future.

Let us return to the investigation of technical flows and check what types of measurement techniques are available for the study of flows in nature. In the following section we will concentrate on those techniques, which are readily available, easy to use and are not specialized to a single application. The main rule for selecting such techniques is that they do not require a probe to be inserted in the flow field with the drawback to influence the flow and/or the natural object.

2 Image-based experimental methods

During the last decade several measurement techniques, which are non-intrusive and image based, such as particle image velocimetry (PIV) and Doppler global velocimetry (DGV) for large field and instantaneous velocity measurements, pressure sensitive paint (PSP) for pressure measurements on the complete surface of a model placed in the flow, and various methods for model location and deformation measurement have been developed. Non-standard video techniques support qualitative visualization as well as the application of the image-based quantitative measurement techniques at high speed or periodic events. Due to the fast progress made in the field of computers, lasers, electronics, video techniques, etc. in the past decade it was possible to set up reliable, modular and mobile advanced measurement systems for use in industrial test facilities such as large wind tunnels. Today PIV and PSP are the most advanced and mostly used of these techniques in industrial wind tunnels, but in other applications in industry and research as well. The qualitative and quantitative improvements achieved during the past few years will be demonstrated in the following sections mainly by presenting results of DLR's applications in industrial wind tunnel tests.

PIV allows the recording of a complete velocity field in a plane of the flow within a few microseconds. Thus, PIV provides information about unsteady flow fields, which is difficult to obtain with standard non-optical and intrusive experimental techniques. PSP provides planar information about the pressure distribution on the surface of the model placed in the flow, not just at a few locations as possible with conventional sensors. Thus, PSP is a very attractive method for application at aerodynamic investigations and also for providing data for comparison with the results of numerical calculations. The short acquisition time and fast availability of data obtained by the advanced experimental techniques reduce the operational time, and hence cost, in large-scale test facilities.

The main areas of application of image-based measurement techniques in aerodynamics at DLR are at present: wake vortices, high lift configurations, delta wings (in rotation) and turbulent and transitional boundary layers. The main problems involved with all these techniques are limited optical access in the closed test section of wind tunnels, reflections from the model under investigation and the time required for setting up and adjusting the equipment and for the calibration of the imaging conditions. Due to its physical properties PSP works better at high speed transonic flows (low pressure) and PIV works better at low speed flows (no problem of velocity lag of tracer particles).

Another problem receiving more and more attention today is that the application of non-intrusive optical measurement techniques such as PIV, DGV, PSP requires the transmitting and receiving optics to be located far away from the object under investigation in order not to disturb the flow. This has the consequence that the instrumentation cannot be rigidly attached to the object under investigation. Especially, if measuring close to the surface of the object the exact position of the area under observation by means of the chosen optical measurement technique and the location of the object are required simultaneously. In addition, models in a wind tunnel to be investigated at high-speed flows will deform under the loads of the flow. In studies concerning problems of aeroelasticity deformations take place deliberately. This means that the location of a model in the wind tunnel as well as its deformation have to be determined carefully during the measurement, especially when applying optical diagnosis tools. In addition, such information is also absolutely required when utilizing these experimental data for validation of numerical calculations. The need to perform model location and deformation measurements in different wind tunnels for different aerodynamic investigations requires developing a modular and mobile system for model deformation measurements as well. All these features such as short time measurement, large scale of flow velocities, parallel measurement of actual shape of object, field information for comparison with numerical results are required for measurement techniques for flows in nature as well.

In anticipation of the description of the various experimental methods given in the following sections, some other well-known image-based methods will be briefly mentioned next and it will be explained why they have not been considered for more detailed description.

For density measurements the classical schlieren method is well known for more than a century. However, its use requires windows of high optical quality, which are very expensive. In Section 2.4, the Background Oriented Schlieren (BOS) method for density measurements will be presented which is much easier to use. Interferometry will also not be discussed here as it involves even more complex optical components and requires considerable skill at set-up and alignment.

The latter argument also holds for holographic methods, which can only be used in laboratory environments. Laboratories specialized on measurement techniques and owning interferometric or holographic systems together with the knowledge how to use them, may also apply them to flow in natures. Scientists who are primarily interested in the flow phenomena in nature should look at easier to use methods first.

Experimental methods for measurement of surface temperature and heat transfer such as infrared thermography, thermocolour, thermosensitive paint, liquid crystal methods are only partially available on a commercial basis with standard evaluation software and in most cases still need a lot of adaptation to the problem to be investigated. For living objects it is difficult to apply any kind of paint to the object. For dead objects, temperature sensitive paint, which uses similar equipment as PSP (Section 2.3) and which is under strong development at present, may become an interesting alternative to classical methods for measurement of surface temperature and heat transfer in future.

2.1 Set-up of non-standard video techniques for qualitative and quantitative flow visualization

The most simple image-based method is the observation of the (natural) flow by means of video cameras. For many decades the main effort at visualizing structures and objects in flows has been to find ways and means to mark the flow with dyes, smoke, tracer particles, etc. and to insert them in a proper way into the flow in order to be able to observe just the desired flow phenomenon. In flows with compressibility effects means had to be found how to transfer density variations in ‘visible’ information. Photographic recordings have been taken for the registration of the visualized flow in order to be able to analyse the observed phenomena in more detail later on. With the availability of video cameras and even more by the availability of easy-to-use, robust and reliable charge coupled devices (CCD), sensors and digital storage media the use of qualitative visualization methods has become more and more popular for the investigation of flows. The size of the observation area required by the dimensions of the object can be easily adapted to the size of the CCD sensor by means of lenses at imaging. However, one has to keep in mind that when selecting a large observation area the local resolution will inversely be decreased, due to the limited pixel number of the CCD sensor – in contrast to pointwise scanning of a flow field by means of a probe. Observation by means of video cameras can take full advantage of existing modern video technique [high speed (up to 1 million frames/s with limited number recordings in ‘burst’ mode), or moderate speed (1000 frames/s with continuous recording)], sophisticated triggering hard- and software to be able to zoom in the phenomenon of interest in time as well, digital storage and later evaluation and post-processing. Geometrical planar features of the flow and the natural object can be visualized by means of well-known image-processing algorithms. However, the information which can be extracted is still more or less qualitative, except in cases where simple parameters of the flow have to be determined, e.g. the trajectory of the distinct core of a vortex, the displacement of tracer particles (PIV), or where image-processing methods can be employed, e.g. to detect and count interference fringes.

Though the number of applications of flow visualization methods and the information available has considerably increased in the past few years, the temporal resolution of today’s visualization methods is still restricted due to technological limits, i.e. the framing rate of the standard video technique of 25 or 30 frames/s. The basic ideas how to overcome these limits and to increase the temporal resolution have been the same as for photographic methods, i.e. for high speed video techniques to increase the number of sensors from 1 to 8 or 16 (like the increase of number of photographic 'sensors' in a drum camera) or for periodic phenomena to employ conditional sampling methods, i.e. stroboscopic illumination. The main drawback of these methods is that in most cases the set-up is quite complicated and that the costs for the equipment are high.

A major break-through for visualization of periodic events (and flows) has been achieved through the development work carried out in the Institute of Aerodynamics and Flow Technology at DLR in the past years. Starting from the development of a high-speed video camera system [1] and of a robust and versatile trigger and synchronization system together with an advanced phase shifter [2] a high-speed video stroboscope has been developed, constructed and tested [3]. Like with the well-known stroboscope a periodic event can be observed at a fixed point in time of the cycle of the periodic event or in slow motion. The main difference as compared to the standard stroboscope is that no shuttered light source for illumination is required but the electronic shutter of the CCD sensor is used to obtain the stroboscopic registration. Together with the available sophisticated triggering electronics and a versatile and user-friendly software a wide area of applications of this high-speed video stroboscope appears not only in flows but quite general for periodic movements of objects.

2.1.1 Synchronization system

Stasicki *et al.* [2] discuss the need for advanced synchronization techniques required, e.g. in order to be able to perform complex flow field investigations by means of PIV (flow fields above a rotor, flow field behind the free-flying model of an airplane, etc.). The conclusions of this discussion apply to the observation of moving, swimming or flying objects in nature as well. Such complex applications have been made possible by means of the sequencer developed at DLR. Technical details of the hard- and software of the sequencer have been presented in [2]. Figure 1 presents the block circuit of the sequencer version 5.0 RS.

The hardware comprises 16 independent output channels with freely programmable pulse width, an internal programmable trigger generator, a second trigger input with pulse number divider, an

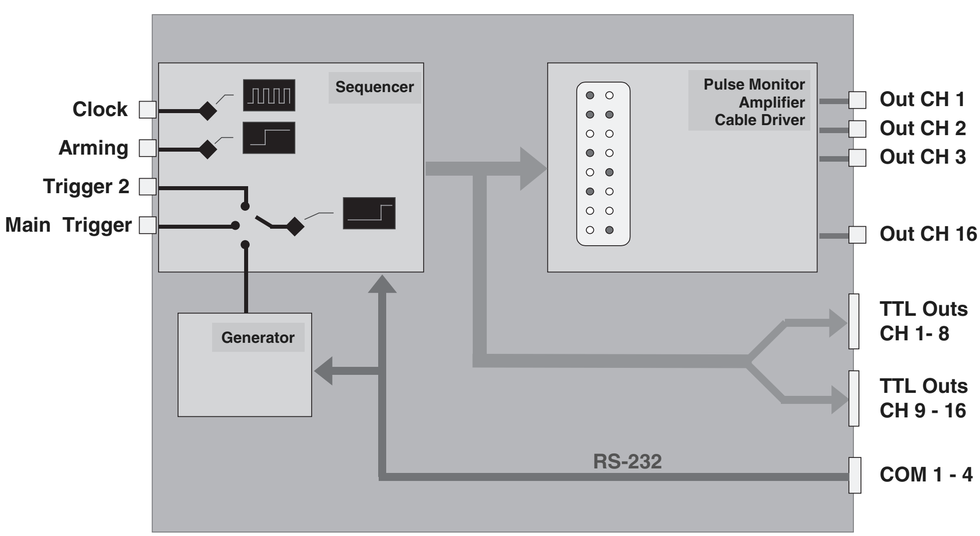

Figure 1: Block diagram of the new sequencer V5.0 RS.

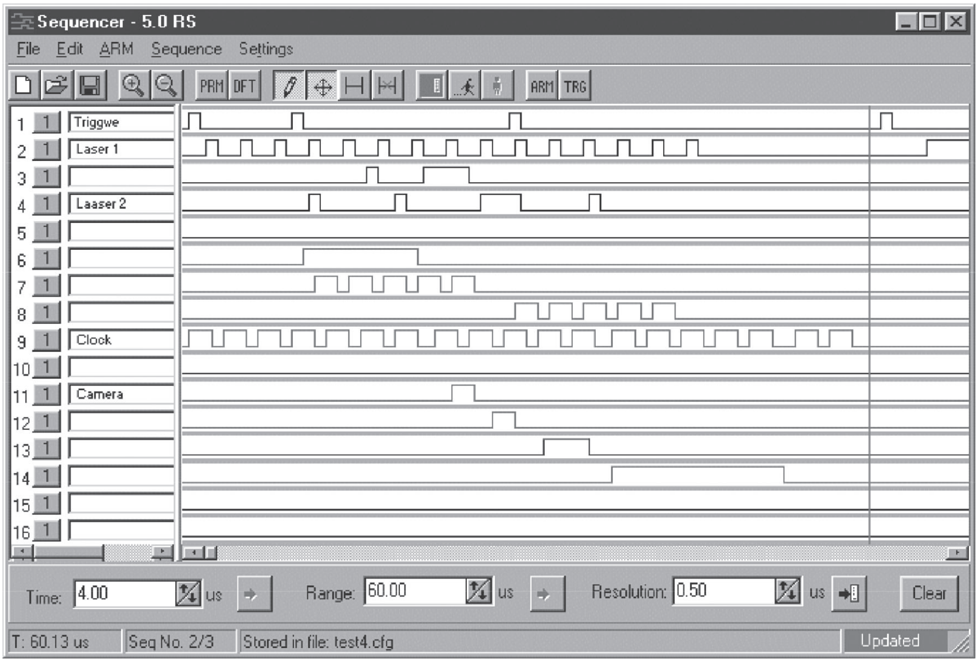

Figure 2: Screenshot of the sequencer V5.0 control software with possibility of graphical editing of timing diagram; red horizontal line: pulse width to be edited.

input to arm the sequencer, etc. The standard output is TTL (transistor–transistor logic), but cable drivers are available for output between 6 and 15 V as well.

A few very important new features have been incorporated in the new control software (see Fig. 2). A graphical user interface displaying the timing diagrams of the pulse trains has been developed. It is now possible to edit the complete timing diagram of the pulsing, including pulse widths and spacing graphically on-screen using the computer mouse. It is also possible to insert new pulses and trains of pulses into existing timing diagrams. Features such as ‘logic inversion of sequence/channel’, ‘zoom-in, zoom-out’, ‘time read-out using mouse cursor’ and ‘trigger source selectable by software (main input, trigger 2, internal generator)’ are available. The user-friendly software runs under standard Windows operating systems.

2.1.2 High-speed video stroboscope

The video stroboscope developed at DLR can be utilized for periodic and non-periodic repetitive high-speed phenomena. The object under inspection can be illuminated by a standard continuous light source, such as daylight or a halogen lamp. No flash lamp is required. Self-luminous objects can be examined as well.

Details about the video stroboscope have been given by Stasicki *et al.* [3, 4]. For the understanding of the applications presented in this section, it is sufficient to know that the video stroboscope system consists of an asynchronously shuttered progressive scan CCD camera, a frequency-independent digital phase-shifter and a PCI-bus frame grabber.

The camera shutter is controlled by external trigger pulses. In response to each trigger pulse, the camera delivers a single frame which is digitized instantly by the frame grabber, stored

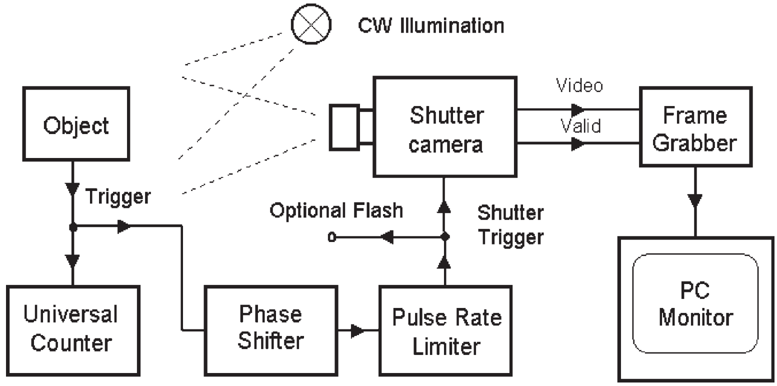

Figure 3: Set-up of the high-speed video stroboscope.

in the computer memory and displayed on the computer monitor. The camera shutter time, i.e. the camera frame integration time, can be set in the range from 1/50 down to 1/800,000 sec. This very short shutter time capability is essential in the case of visualization and recording of extremely fast objects, in order to prevent blurred images. The trigger pulses are picked-up from the investigated event using an appropriate sensor (pressure transducer, microphone, photo cell, Hall-sensor, jitter-free contact and so on). To obtain the slow-motion effect, a phase shifter circuit is placed into the trigger signal path. This frequency independent, digital phase shifter has been developed specially for this purpose [5]. It can operate in two modes: phase-shift mode, which is convenient for periodic events and delay mode used to examine non-periodic but repetitive events.

Figure 3 presents the set-up of the high-speed video stroboscope for an object of self-running type. In this case it is necessary to detect the movement of the object with an appropriate sensor in order to obtain the trigger pulse for the synchronization of the video stroboscope. An example of this kind of triggering would be the visualization of the movement of a turbine or a propeller, or in case of living objects the visualization of the movement of the human larynx or of a grasshopper (see examples in Sections 2.1.3.1 and 2.1.3.2). The other possibility (not shown here) would be that the investigated object has to be controlled by an external control signal. Such a signal can easily be provided by the video stroboscope's frequency synthesizer. An example of this kind of application would be an electrically controlled fuel injection nozzle [6].

Both the phase shifter and the frame grabber are located in the industrial PC (see Fig. 4). As option, a universal counter and a frequency synthesizer can be added for control purposes. All components of the system (camera, frame grabber, digital phase shifter, frequency synthesizer and the universal counter) are controlled by integrated software running under W9x, 2K and XP.

During the measurement the image of the stroboscopically inspected event is displayed live on the monitor of the PC. The shutter of the camera is triggered by the event via the phase shifter, which can be programmed to change the phase shift slowly in order to realize a slow motion effect in real time. The timing required to obtain this feature is shown in Fig. 5. The upper part represents a harmonic event. That part of this curve, which is circled, shall be examined in detail using a slow-motion display. It is assumed, that the event delivers one trigger pulse per period (indicated by the vertical lines) by positive-going zero crossings. The phase shifter is programmed in such a way, that the first image (represented by vertical lines) will be taken at an initial phase shift of Φ_0, the second one at a phase shift of $\Phi_0 + \Delta\Phi$, the third one at a phase shift of $\Phi_0 + 2\Delta\Phi$, the fourth at $\Phi_0 + 3\Delta\Phi$ and so on until the event of interest (indicated by the circle) has been completely scanned (of course, the full cycle can be scanned as well). The result, the time resolved periodic event, is represented by the steps, which are displayed in the lower part of Fig. 5. It should be kept in mind, that the apparent speed of the displayed movement can be programmed freely by the user and does not depend on the frequency (nor its changes) of the real event.

Both, the phase shift and the slow motion period are selectable, independently of the real frequency of the event. Non-periodic but repetitive events can be observed in an alternate time delay mode of the phase shifter. The camera exposure time can be varied between 1.25 μs and 16 ms. It allows the stroboscopic observation of very fast oscillating (above 10 kHz) and rotating (up to 100.000 rpm) objects. Sequences of up to 5000 frames each can be stored on the hard disc drive for documentation, evaluation, post-processing and playback. Each picture has a maximum resolution of 760 pixels × 580 pixels at 256 grey levels.

Figure 4: Video stroboscope work station.

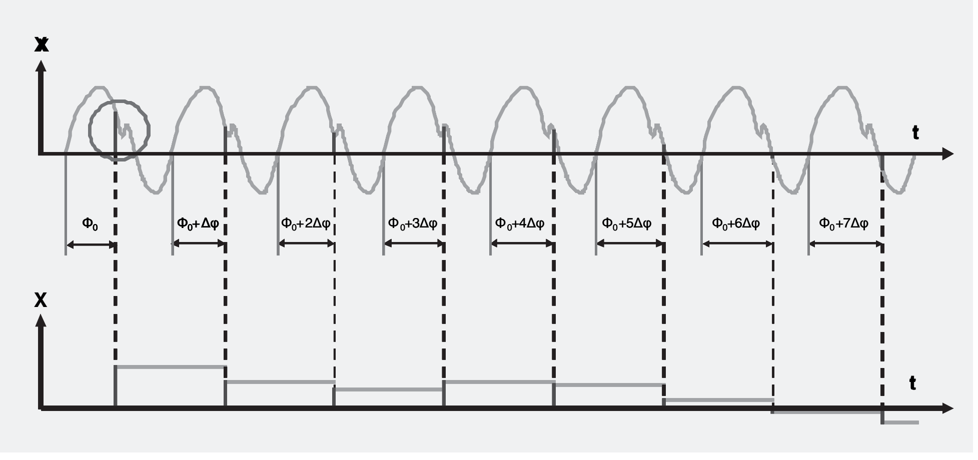

Figure 5: Timing of pulse shift required obtaining 'slow motion' effect. Upper part: sketch of periodic event, with time of triggering (dotted vertical line) and position of object (vertical line). Lower part: output of video stroboscope: position of object (vertical line) visible for one frame (length of horizontal line).

For easy documentation each of the captured and stored pictures is labelled with the most important parameters of the investigated object, the settings of the stroboscope and the date and time of recording. These parameters are displayed on the screen during the observation of the object and during the recording and play back of the stored pictures and sequences.

A built-in user programmable look-up table enables the pseudo-colour display of the frames. In some cases this may help to better recognize the shape of the investigated objects and to follow their movements.

Unsteady objects having a temporal/phase jitter or/and spatial fluctuations can be investigated using the real-time frame averaging routines added to the software. For application of the video stroboscope employing the BOS method [7], for the measurement of density gradients or the Image Pattern Correlation Technique (IPCT)/Projected Pattern Correlation Technique (PROPAC) for the measurement of model deformation [8], a reference picture can be stored as well. A multi-camera version of the video stroboscope has been developed, which allows monitoring large scale objects (e.g. the movement of the gap width of the flaps of the wing of an airplane [9]).

2.1.3 Application of the high-speed video stroboscope

In this section a few representative examples for the application of the high-speed video stroboscope for qualitative and quantitative visualization will be given.

2.1.3.1 Inspection of human larynx The video stroboscopic investigation of the larynx has become a powerful tool for the study of vocal physiology, assessment of the fold abnormalities, motion impairments and functional disorders, as well as for the early diagnosis of diseases like cancer and pathologies like nodules, carcinoma, polyps and cysts. Since the vocal folds vibrate in the range of 100 Hz up to 1 kHz, the video stroboscope allows physicians to find otherwise undetectable problems.

Stasicki and Meier [10] give details about the application of the video stroboscope to the inspection of the human larynx. Figure 6 shows a picture of the human larynx, when a human (male) voice generates sound of 200 Hz. This picture has been extracted from a sequence of 300 full frames, recorded in the phase-shift mode. Stroboscope synchronization was performed by means of a microphone. The digital phase shifter used in the video stroboscope takes care that the phase shift stays constant even if the frequency of the voice generation changes slowly during

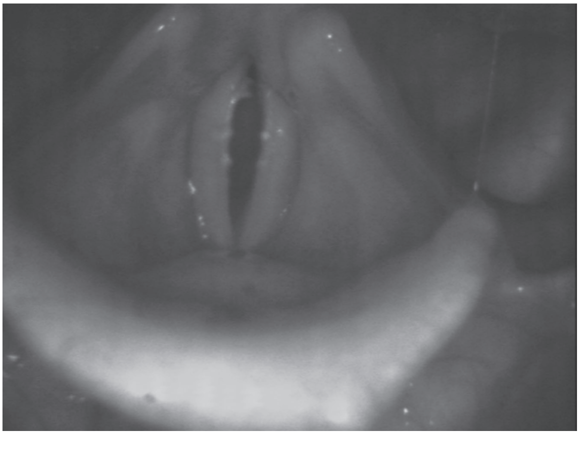

Figure 6: Vibrations of human larynx, recorded by means of the high-speed video stroboscope.

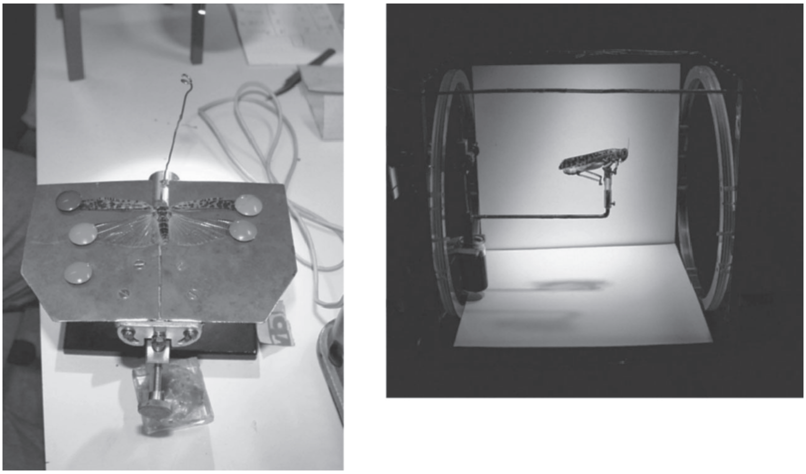

Figure 7: Application of triggering devices to the grasshopper (left) and small wind tunnel with grasshopper (right).

the recording. The shutter time was 1/10,000 sec. The larynx was illuminated with a halogen lamp 12 V/20 W via an optical fibre. The results achieved with the monochrome high-speed video stroboscope have encouraged developing a medical colour version. The main reason for this is that the early cancer diagnostics requires a high colour resolution of the system since the cancer in its early stage can be detected as a small spot of a slightly different hue.

2.1.3.2 Flight of grasshopper The study of flight of insects, e.g. grasshopper, has been supported by means of the slow-motion video imaging. The living animal was fixed with a droplet of colophony to the metal holder and placed in the test section of the wind tunnel (Fig. 7, right). The holder was mechanically connected to the three-dimensional balance which allows to register the lifting forces generated by the animal during the flight. The wind tunnel air speed has been varied in the range of 1 up to 5 m/s. The synchronization of the video stroboscope was performed by means of the electrical pulses coming from the ultra miniature coils made of a 5 μm wire and fixed to the wings of the examined insect, for which a magnetic field was generated in the test section of the wind tunnel. However, due to relatively low wingbeat frequency of the grasshopper of about 23 Hz the manual synchronization of the system using an external frequency generator was favoured because the attachment of the coils to the insect wings was an extremely sophisticated and time consuming task (Fig. 7, left). A simple halogen lamp of 20 W was used to illuminate the object. The exposure time of the camera was set to 1/10,000 sec. On the basis of acquired image sequences the movement of the insect's wings, the phase shift between the front and rear wing pairs and the mechanisms of performing the manoeuvres has been studied (Fig. 8).

2.1.4 Potential of the high-speed video stroboscope for investigation of natural flows

The high-speed video stroboscope developed, constructed and applied at different investigations in aerodynamics by DLR allows performing qualitative and quantitative visualization of periodic events. The high interest in the unique features of the high-speed video stroboscope and the immediate possibility for application in the most different areas, have led to several applications by DLR outside aerodynamics from which the examples presented here have been taken.

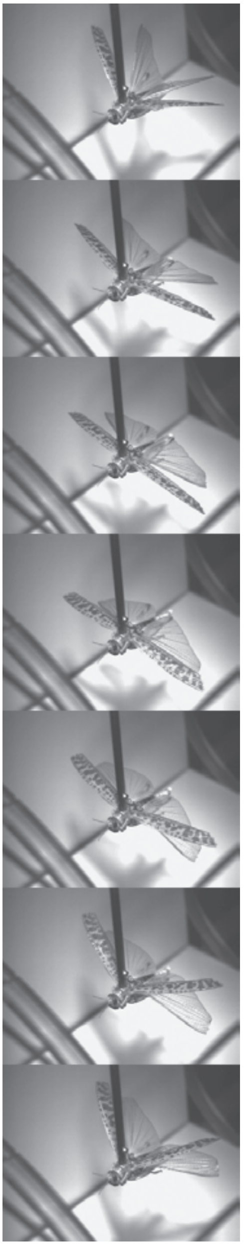

Figure 8: Time sequence of flight of a grasshopper. Framing rate 230 frames/s.

The video stroboscope being a purely visual technique is of general applicability for flows in nature. Problems may occur in situations where strong light sources for illumination are required or if the trigger signal from the living object cannot be obtained contact less. The extension of the system to four cameras allows different areas of the object with a magnification adapted to the area of interest to be investigated instantaneously at the same moment.

2.2 Particle image velocimetry

PIV enables the instantaneous measurement of a large number of velocity vectors. A detailed description of the PIV technique is given by Raffel *et al.* [11]. Employing PIV in its 'classical' form, the information about magnitude and direction of an instantaneous velocity vector is determined from the displacement of the images of tracer particles, illuminated in a plane of light within the flow.

The PIV technique is under development for more than 20 years. In the past few years it has become a standard technique for application in many different areas in research and industry (aerodynamics, turbomachinery, engines, chemical industry, oceanography, micro-flows, biology (fish), medicine (artificial heart valves, blood vessels). Stereoscopic PIV, which allows obtaining all three velocity components simultaneously in a plane of the instantaneous flow field can be applied in all experimental set-ups with adequate optical access. Modern high resolution video cameras allow obtaining velocity fields of several thousand vectors each with recording rates of 3–5 recordings/s over long periods of time, enabling the determination of the statistics and spatiotemporal correlation of turbulent flows. Recent developments of evaluation algorithms include multi-grid and window deformation techniques, providing much better spatial resolution in the core of a vortex or for gradients in a boundary layer.

2.2.1 Set-up of PIV

Figure 9 briefly explains a typical set-up for PIV recording in a wind tunnel. Small tracer particles are added to the flow. A plane light sheet within the flow is illuminated twice by means of two laser pulses of the same wavelength and of the same (short) pulse length, which are delayed by a time interval τ, which may be as short as few microseconds. The images of the particles due to the first and second exposure are registered by a CCD sensor in two subsequent frames of the video signal. The output of the CCD sensor is stored in real time in the memory of a computer directly. For evaluation the digital PIV recording is divided in small sub areas called 'interrogation areas'. It is assumed that all particles within one interrogation area have moved homogeneously between

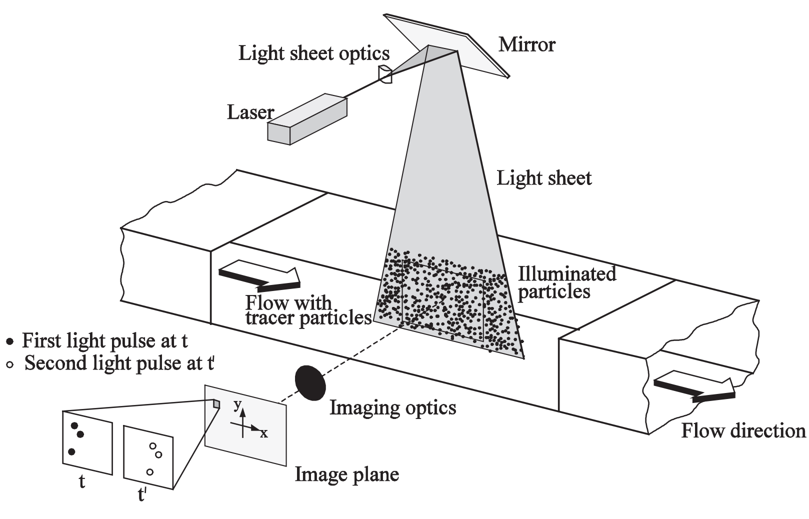

Figure 9: Experimental arrangement for PIV in a wind tunnel.

the two illuminations. The local displacement vector for the images of the tracer particles of the first and second illumination is determined for each interrogation area by means of by particle tracking, or locally applied statistical methods (cross-correlation). The projection of the vector of the local flow velocity into the plane of the light sheet (2-component velocity vector) is calculated taking into account the time delay τ between the two illuminations and the magnification M at imaging.

The process of interrogation is repeated for all interrogation areas of the PIV recording. With modern video cameras (1000×1000 sensor elements) it is possible to capture about 10 PIV recordings per second, for high speed PIV systems with special lasers and CCD sensors even up to 1000 PIV recordings per second are possible. The evaluation of one video PIV recording with 3600 instantaneous velocity vectors (depending on the size of the recording and of the interrogation area) is of the order of a few seconds with standard computers.

2.2.2 Features of PIV

In the following some general aspects of the PIV technique will be discussed.

Non-intrusive velocity measurement. In contrast to techniques for the measurement of flow velocities employing probes as pressure tubes or hot-wires, the PIV technique being an optical technique works non-intrusively. This allows the application of PIV even in high-speed flows with shocks or in boundary layers close to the wall, where the flow may be disturbed by the presence of probes.

Indirect velocity measurement. In the same way as with laser Doppler velocimetry the PIV technique measures the velocity of a fluid element indirectly by means of the measurement of the velocity of tracer particles within the flow, which – in most applications – have been added to the flow before the experiment started. In two-phase flows particles are already present in the flow. In such a case it will be possible to measure the velocity of the particles themselves as well as the velocity of the fluid (to be additionally seeded with small tracer particles).

Whole field technique. PIV is a technique that allows one to record images of large parts of flow fields in a variety of applications in gaseous and liquid media and to extract the velocity information out of these images. This feature is unique to the PIV technique. Except DGV, which is a technique particularly appropriate for high-speed airflows, all other techniques for velocity measurements only allow the measurement of the velocity of the flow at a single point, however in most cases with a high temporal resolution. With PIV the spatial resolution is large, whereas the temporal resolution (frame rate of recording PIV images) is limited due to technical restrictions. These features must be observed if comparing results obtained by PIV with those obtained with traditional techniques. Instantaneous image capture and high spatial resolution at PIV allow the detection of spatial structures even in unsteady flow fields.

Velocity lag. The need to employ tracer particles for the measurement of the flow velocity requires us to check carefully for each experiment whether the particles will faithfully follow the motion of the fluid elements, at least to that extent required by the objectives of the investigations. Small particles will follow the flow better.

Illumination. For applications in gas flows a high power light source for illumination is required in order that the light scattered by the tiny tracer particles will expose the video sensor. However, the need to utilize larger particles because of their better light scattering efficiency is in contradiction to the demand to have as small particles as possible in order that they follow the flow faithfully. In most applications a compromise has to be found. In liquid flows larger particles can usually be accepted which scatter much more light. Thus, light sources of considerably lower peak power can be used here.

Duration of illumination pulse. The duration of the illumination light pulse must be short enough that the motion of the particles is ‘frozen’ during the pulse exposure in order to avoid blurring of the image (no ‘streaks’).

Time delay between illumination pulses. The time delay between the illumination pulses must be long enough to be able to determine the displacement between the images of the tracer particles with sufficient resolution and short enough to avoid particles with an out-of-plane velocity component, leaving the light sheet between subsequent illuminations.

Distribution of tracer particles in the flow. At qualitative flow visualization certain areas of the flow are made visible by marking a stream tube in the flow with tracer particles (smoke, dye). According to the location of the seeding device the tracers will be entrained in specific areas of the flow (boundary layers, wakes behind models, etc.). The structure and the temporal evolution of these structures can be studied by means of qualitative flow visualization. For PIV the situation is different: a homogeneous distribution of medium density is desired for high quality PIV recordings in order to obtain optimal evaluation. No structures of the flow field can be detected on a PIV recording of high quality.

Number of components of the velocity vector. Due to the planar illumination of the flow field only two (in plane) components of the velocity vector can be determined in standard PIV (2C-PIV). Methods are already available to extract the third component of the velocity vector as well (stereo techniques, dual-plane PIV, holographic recording). This would be labelled 3C-PIV. Both methods work in planar domains of the flow field (2D-PIV).

Extension of observation volume. In the most general way an extension of the observation volume is possible by means of holographic techniques (3D-PIV). Other methods such as establishing several parallel light sheets in a volume or scanning a volume in a temporal sequence would be referred to as 2.5D-PIV.

Extension in time. By means of repetitively working cameras it is already possible to record temporal sequences of PIV recordings. However, as the repetition rate of pulse lasers and cameras is limited, it is not possible to record fast enough as would be required due to the temporal scales of most technical flows (frequencies in the range of several kHz).

Size of interrogation area. The size of the interrogation area at evaluation must be small enough that velocity gradients have no significant influence on the results. Recently developed multi-grid and window deformation techniques have considerably helped to improve the situation. Furthermore, the size of the interrogation area determines the number of independent velocity vectors and therefore the maximum spatial resolution of the velocity map which can be obtained at a given spatial resolution of the sensor employed for recording.

2.2.3 Application of PIV

In the following two examples for the application of PIV will be given: the first one demonstrating the progress to be gained by quantitative visualization as compared to qualitative visualization and the second showing state-of-the art application of PIV in a wind tunnel, utilizing complex and expensive equipment. For information about application of PIV in nature reference is made to the contribution ‘Shedding light on animal-generated flows: quantitative analysis of animal-generated flow patterns using DPIV’ by E. Stamhuis in this book.

2.2.3.1 Unsteady flow-above profile A great step forward in the investigation of flows was made after it was possible to replace such passive observations of nature by experiments carefully planned to extract information about the flow utilizing visualization techniques. A well-known promoter of such a procedure was Ludwig Prandtl, one of the most prominent representatives

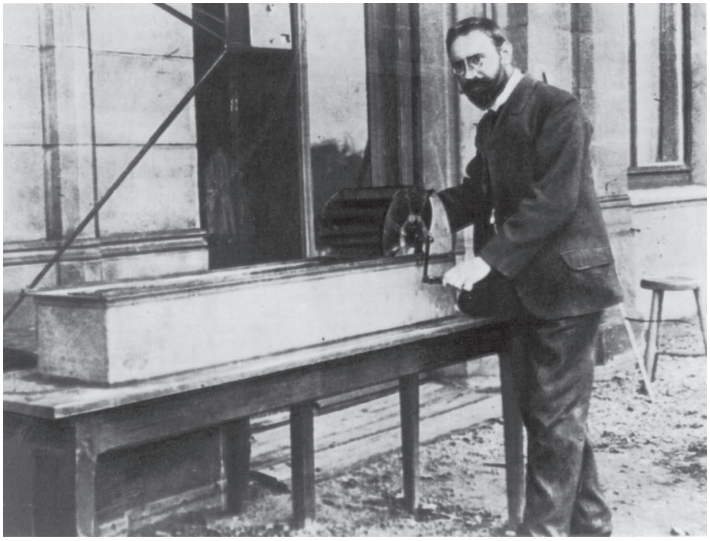

Figure 10: Ludwig Prandtl in front of his water tunnel for flow visualization in 1904.

of fluid mechanics, who designed and utilized flow visualization techniques in a water tunnel to study aspects of unsteady separated flows behind wings and other objects.

Figure 10 shows Ludwig Prandtl in 1904 in front of his tunnel, driving the flow manually by rotating a blade wheel. The tunnel comprises an upper and lower section separated by a horizontal wall. The water recirculates from the upper open channel, where the flow may be observed, back through the lower closed duct. Two-dimensional models like cylinders, prisms, and wings can be easily mounted vertically in the upper channel, thereby extending above the level of the surface of the water. The flow is visualized by distributing a suspension of mica particles on the surface of the water.

Ludwig Prandtl studied the structures of the flow in steady as well as in unsteady flow (at the onset of flow) with this arrangement. Being able to change a number of parameters of the experiment (model, angle of incidence, flow velocity, steady–unsteady flow) Prandtl gained insight into many basic features of unsteady flow phenomena. However, at that time only a qualitative description of the flow field was possible. No quantitative data about flow velocity could be achieved.

Today, one hundred years after Ludwig Prandtl's experiments, it is easily possible to also extract quantitative information about the instantaneous flow velocity field exactly from the same kind of images as were available to Prandtl. A proof for this is given in Fig. 11. A replica of Ludwig Prandtl's water tunnel together with a flash lamp for illumination and a video camera have been employed to obtain a visualization of the flow by means of aluminium particles distributed on the water surface.

Evaluation of this recording by cross correlation methods resulted in a vector map of the instantaneous velocity field shown in Fig. 12. This means that the basic principles underlying the PIV, which is just a quantitative visualization technique, have already been known for a long time.

However, the scientific and technical progress achieved in the last 100 years in optics, lasers, electronics, video and computer techniques was necessary to further develop a technique for qualitative flow visualization to such a stage that it can be employed for quantitative measurement of complex instantaneous velocity fields.

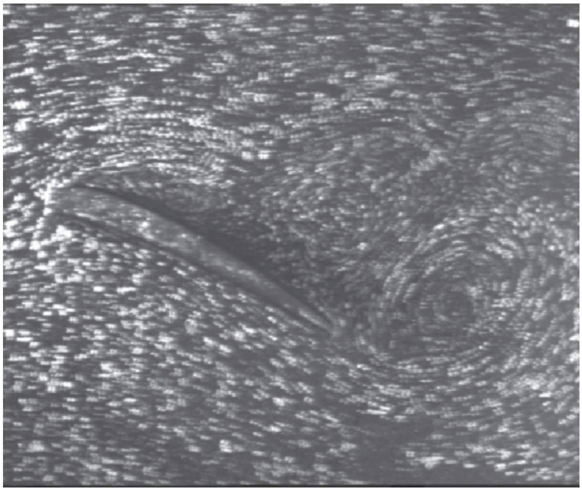

Figure 11: Separated flow behind wing, visualized with modern equipment in a replica of Ludwig Prandtl's tunnel.

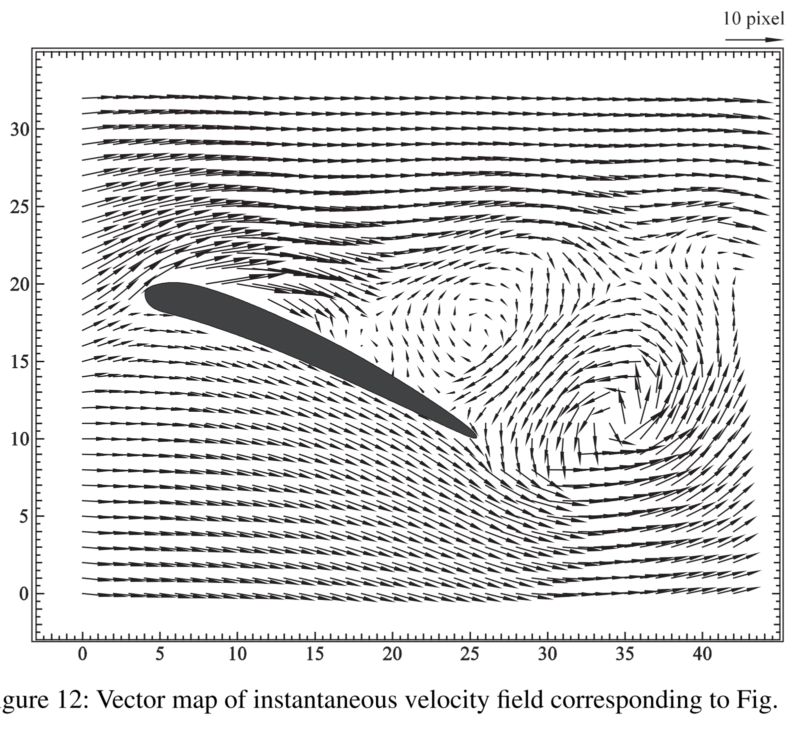

Figure 12: Vector map of instantaneous velocity field corresponding to Fig. 11.

2.2.3.2 High-lift configurations Investigations of complex flow fields such as the wing/flap flow on both sides of a high-lift configuration with boundary layer, shear layer and separated flows can be performed if a two-laser multi-camera PIV system is available. Such tests have been performed in the frame of the EUROLIFT and EUROPIV 2 projects, carried out in the

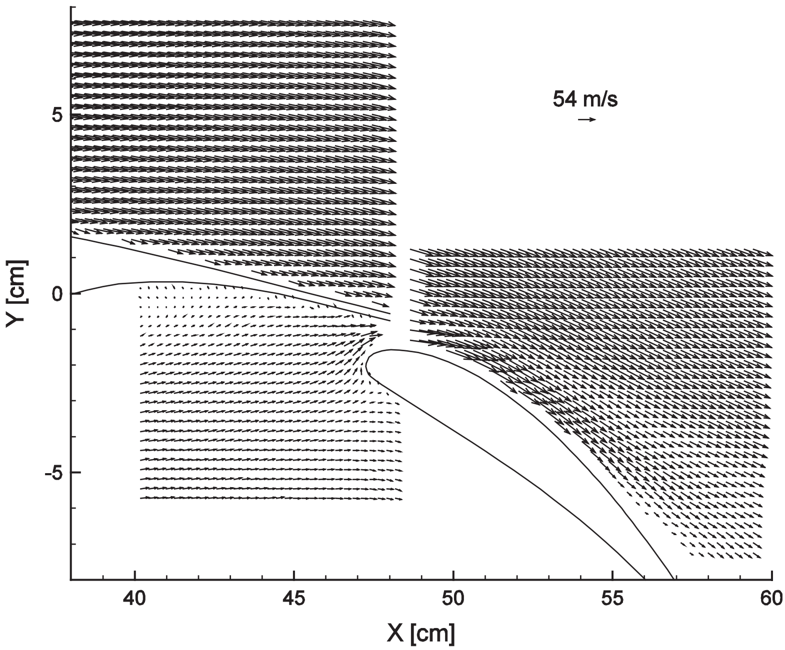

Figure 13: Average velocity fields around the flap of a high-lift configuration (results of EUROPIV 2).

LSWT AIRBUS Bremen wind tunnel [12]. The use of several cameras to capture the flow-field in different regions around the model simultaneously has many benefits for the comparison of experimental results with numerical codes. The observation areas of the multi-camera PIV measurements have been adapted to the model contour. Averaged velocity fields can be seen in Fig. 13. To adapt the PIV system to the requirements of measurements of high-lift configurations two-axis Scheimpflugadapters have been developed at DLR to increase the degree of freedom on optical access. This will become necessary especially for stereo (3C-) PIV measurements on flows around 3D-airfoils with swept wing and complex slat and flap settings.

2.2.4 Potential of PIV for investigation of natural flows

Many successful applications of PIV in biology, medicine, oceanography, observation of flow in rivers demonstrate the great potential for PIV as an easy to implement measurement technique for velocity fields in nature at moderate costs. The scale of application ranges from millimetres to kilometres, from microseconds to hours, in most cases possible with the same equipment comprising a pulsed-light source and a high sensitive, high-resolution video camera. Problems at the application of PIV to flows in nature are besides those which are intrinsic to PIV, the problem of tracers (toxicity) and effects of the pulsed illumination on living objects.

2.3 Pressure sensitive paint

For the development of aircraft, pressure measurements for load evaluation and for flow field analysis are indispensable. Conventional techniques employing pressure orifices and transducers result in high cost and a lengthy fabrication time of the model. Moreover, they provide pressure information only at the location of the pressure taps, which have to be defined at the time of the construction of the model a long time before the aerodynamic investigation. Thus, non-intrusive pressure measurements using PSP, which provides planar pressure information on the surface of the model play more and more an important role in aerodynamics.

In contrast to conventional methods PSP is an optical method [13]. It is based on a thin layer of special paint molecules on the surface of the model. The paint is illuminated by UV light and emits fluorescence light in the visible range. The intensity is lowered by the amount of oxygen molecules which are present at the surface due to the local surface pressure. Pressure data are therefore available all over the surface. A few pressure data from conventional pressure transducers provide data for calibration and monitoring purposes but no extensive drilling of holes and tubing of the model is necessary.

Various paints as single- and two-colour versions exist including different hard- and software. Up to now the best results have been obtained with PSP in transonic speed ranges because of the high absolute pressure differences. The main challenge to get acceptable PSP results, on one hand, is the arrangement of hardware, components of model illumination and camera observation – especially in the handling of eight simultaneously operating CCD cameras, which are required to obtain PSP data on all sides of the model at the same time (360° PSP), see [14]. On the other hand, the software should be able to handle in a short time all the necessary synchronization between the PSP system and the wind tunnel, the acquisition of the PSP images, correction of lens errors, consideration of model deformation, etc. DLR has developed its own software for evaluation of PSP images (ToPas), including all these features.

2.3.1 Application of PSP

2.3.1.1 Transonic flow Figure 14 presents the results obtained with PSP in transonic flow on the EADS MAKO model in the test section of DNW-HST in Amsterdam [14]. The features of the pressure distribution at the nose, the wing and the flaps can clearly be identified.

For the design of an aircraft with very wide flight envelope, both in speed and angle of attack, it is necessary to establish a very large database for pressure data and aerodynamic loads. This database can be obtained experimentally in wind tunnels. Different conventional diagnostic techniques are used in wind tunnel tests depending on the purpose of the investigation and on the nature of the flow, e.g. single-point pressure transducers for pressure data and internal and external balances for aerodynamic loads.

An alternative possibility to get this database for an aircraft is the use of PSP in the 360° set-up. By integration of the pressure data on the complete model or parts of it the respective forces and moments can be calculated. The remarkably good agreement between the moment as obtained with an internal balance and the moment as obtained by integration of pressure data for the horizontal tail of the fighter aircraft is shown in Fig. 15.

2.3.1.2 Low speed flow At present a major part of the present development work at DLR aims at the application of PSP in low speed flows and for unsteady flows. Applications of PSP in low speed flows have already been successfully performed, e.g. for the investigation of the flow field on a propeller aircraft. The accuracy achievable is not yet comparable with that of conventional pointwise measuring methods (pressure holes). The reason is mainly related to the properties of available PSPs, whereas the illuminating and imaging equipment and the evaluation algorithms are readily available. PSPs need to be tailored to the special application (pressure and temperature range, response time, etc.). By close cooperation with chemists developing such paints for the needs of the PSP technique major progress can be expected within the next years.

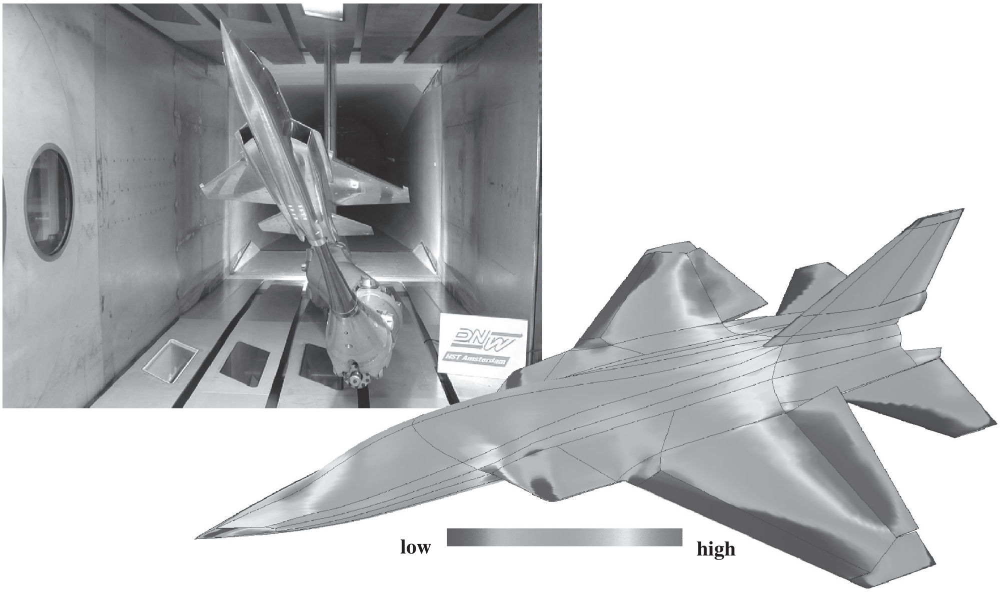

Figure 14: Model in the test section of the transonic DNW-HST wind tunnel and pressure distribution on the model surface.

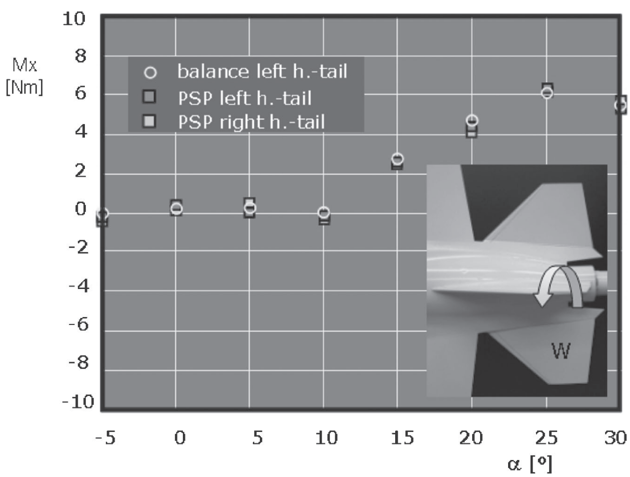

Figure 15: Comparison of bending moment of the horizontal tail, integrated pressure from PSP versus internal balance.

2.3.2 Potential of PSP for investigation of natural flows

The potential for applying PSP to flows in nature for cases where the paint is applied to 'dead' objects is high. The costs of the paint decreasing even large objects can be coated. No potential for application of PSP is seen for living objects with presently available toxic paints.

2.4 Density measurement techniques

Image-based measurement techniques for visualization of density fields, such as the schlieren technique, are in use in wind tunnels on a routine basis for many decades. For quantitative determination of density gradients in flows, as integrated along the path of light through the flow, the relationship between the density and the index of refraction as described by the Gladstone–Dale formula is used. The application of the schlieren technique, however, is hampered by the fact, that expensive high quality windows are required in the wind tunnel test section and that the optical alignment of the schlieren system requires some expertise. In contrast, the background oriented schlieren (BOS) method, developed at DLR since a few years, is much more robust, requires standard equipment only and can be easily used as mobile system as well. A BOS measurement is performed by taking two images of a background with a random dot pattern observed through the density object in the wind tunnel test section. The first image is taken as a reference image with the flow not present, while the second image (the measuring image) is taken with the flow present. Due to the density gradients the index of refraction is different at different locations in the flow field. Therefore the background image, when observed at the imaging plane, will be distorted and the dots will appear at different locations in the two images. The apparent shift can be determined by dividing the images into small interrogation windows and using cross-correlation algorithms as used for PIV. This shift is a measure for the line integral of the density gradients between camera and background whereupon the set-up is sensitive only to the fractions of the density gradient which are perpendicular to the line of sight. Figure 16 shows the principle of a BOS set-up.

2.4.1 Application of the BOS method

The possibility of obtaining quantitative density data by means of BOS for circular density objects can best be demonstrated with a free jet experiment in air. The density inside the jet was measured with the BOS method and for comparison with an interferometer at the same time. Since both methods measure the line of sight integral the density distribution can only be determined using special algorithms and a certain kind of symmetry or using a number of measurements and a tomographic algorithm. In this case, taking the rotational symmetry of the jet into account, an algorithm known as the 'onion peeling method' was used. In Fig. 17 (left) the results obtained by application of the cross correlation algorithm is shown. The vectors indicate the strength and the direction of the line of sight integrals of the density gradients. For the line indicated in Fig. 17 the density distribution has been calculated. The result is shown in Fig. 18 as the dimensionless density over the jet radius.

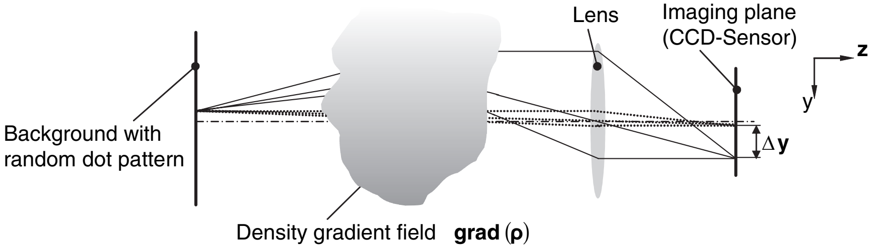

Figure 16: Experimental set-up for BOS measurement.

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The BOS method has also been successfully applied to the location and assessment of the strength of wing tip vortices in transonic flow (DNW–TWG), in combination with the PIV technique [7].

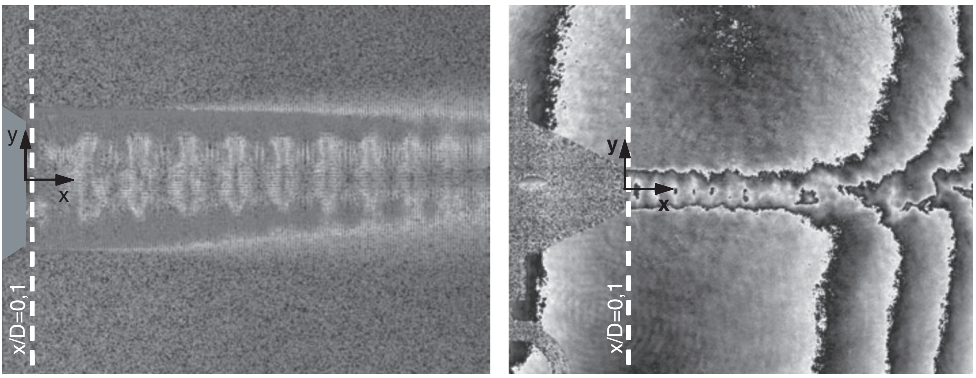


Figure 17: Results of BOS (left) and interferometer (right) measurement for a jet flow.

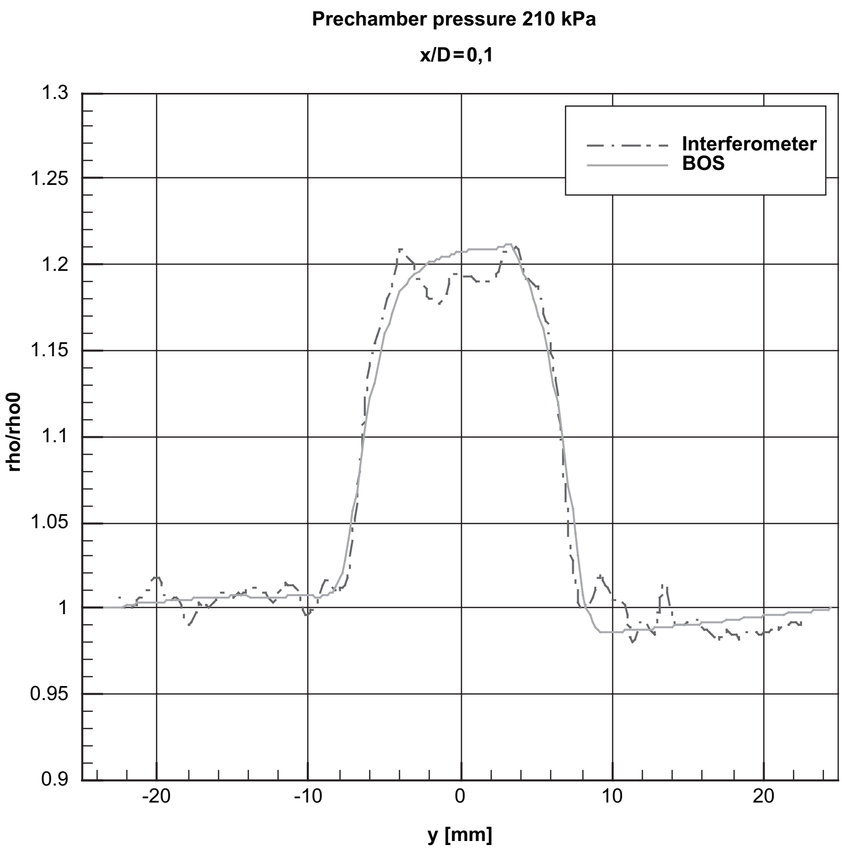


Figure 18: Density distribution inside the jet.

2.4.2 Potential of the BOS method for investigation of natural flows

As an easy-to-use low-cost method BOS has great potential for flows in nature as well. In contrast to aerodynamics strong gradients in high-speed airflows will most likely not occur in nature, but density gradients due to different temperature (in air and water) and due to different concentration (different gases in air, salinity in water, etc.) can easily be studied by BOS without any effects on living objects.

2.5 Position and deformation measurement techniques

The need to measure model location and deformation has already been explained. However, no general-purpose method exists up to now due to the requirements of the different applications. For monitoring a model in the test section of a wind tunnel it is sufficient to record with standard video rate (25 Hz), whereas the measurement of the location of a propeller or rotor blade or of a manoeuvring model requires much higher recording rates. Under wind load a model usually experiences a large displacement (dc component) plus a small scale unsteady displacement due to model vibrations or the aeroelastic behaviour of the model. At present this requires different techniques for measurement of model location and deformation. Several methods are under development at DLR Göttingen for use in wind tunnels at present:

2.5.1 Combined model position detection and deformation analysis (POSI)

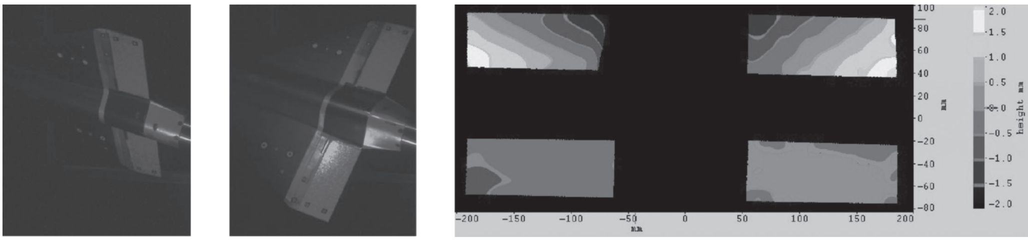
A combined 3D position detection and 3D deformation analysis system is utilized to measure geometrical properties of moving objects [15]. A synchronized multi-camera system allows for the acquisition of images both at independent observation areas or along an extended trajectory of the object.

For *position detection* reflective markers placed on the model surface are detected by optical triangulation from stereoscopic images of the object. Their actual location during a test campaign is numerically mapped on a CAD surface model of the object under investigation. As a result, the position and movement of the whole object can be displayed on a computer monitor and can be further utilized to define boundary conditions for the geometry of parallel CFD studies.

With *deformation analysis* areas on the test object which are suspected to suffer deformation are covered with a random dot pattern. By means of stereoscopic pattern correlation the deformation of the object surface relative to a reference surface can be measured with high accuracy. This method being fully 3D it also allows for the determination of the absolute surface shape of a test object.

A *combined position and deformation detection* is utilized if the deformation of a moving object has to be measured. The movement of the model can be understood as a movement of the frame of reference in deformation analysis. With reflective markers placed on rigid parts of the model this frame of reference can be detected and can be virtually fixed. As a result the relative deformation of the model in different frames of reference can be measured.

The example presented in Fig. 19 shows the deformation of flaps on an aircraft model determined from combined position detection and deformation analysis. The frame of reference, the model, is manoeuvring during the test. This application takes full advantage of the combined systems' capabilities. That is, the frame of reference is recovered by the tracking of reflective markers, while the flaps' deformation is determined from cross-correlation of a random dot pattern on their surface. The deformation analysis reveals a considerable deflection of both flaps at $Ma = 0.85$ under changing wind load during the roll manoeuvre. It is compared to the same analysis when no wind load is present.



β = 225° β = 303° without wind load (bottom) and with wind load (top)

Figure 19: Combined position (left) and deformation (right) detection of flaps on rotating delta wing.

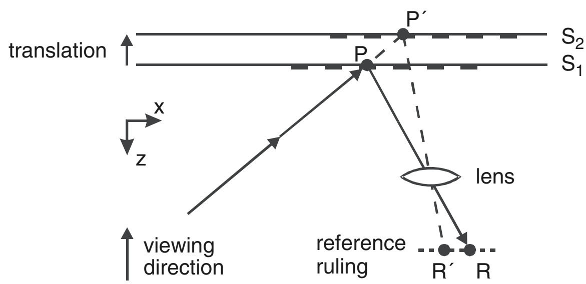


Figure 20: Moiré measurement model for the acquisition of deformations in viewing direction.

2.5.2 Moiré interferometry technique

A system for high-resolution model deformation measurement is of special importance for wind tunnels such as cryogenic European Transonic Windtunnel (ETW), when Reynolds number effects shall be studied. Without disturbing the flow, the movements, deformations and vibrations of a model in a wind tunnel can be precisely determined by Moiré interferometry [16]. This technique uses the interference of periodic patterns to measure the topology of a given surface. The measurement principle is illustrated in Fig. 20.

A Ronchi ruling with parallel black and transparent stripes of equal width is projected onto a plane surface S_1, and the image of the stripes is focused onto a reference ruling. The stripes of the imaged and the reference ruling are parallel to each other, and superimpose to a Moiré interferogram. If the surface is then translated to location S_2, the stripes on the surface move in the x-direction, and a projection ray indicated in Fig. 20 shifts on the surface from P to P′. P′ in turn is now focused onto R′, thus producing an interference pattern with a different intensity.

A translation of the surface in the x- or y-direction does not lead to a shift of the ruling focused onto the surface, and so does not influence the interferogram. The technique is therefore only sensitive to translations in z-direction.

If the observed surface is curved, the resulting fringes in the Moiré interferogram represent lines of equal elevation. This implies that large surface gradients lead to large spatial fringe frequencies in the interferogram. Figure 21 shows the Moiré pattern on the wing (lower side) of the HiReTT full span model in the ETW.

The distance in z-direction between two adjacent Moiré fringes is called the layer distance, which is a function of the optical set-up and usually has to be determined by a calibration measurement. By using image-evaluation algorithms the topology of the surface can be determined

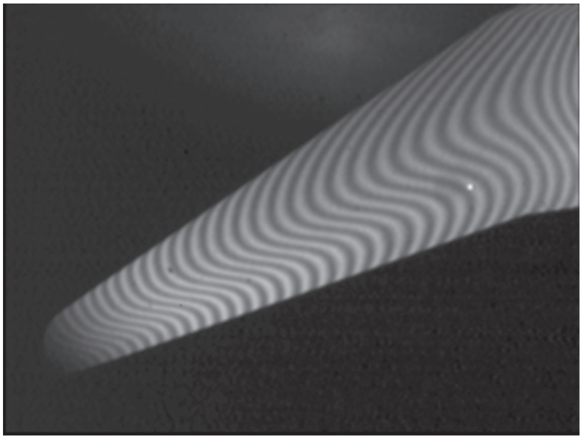


Figure 21: Moiré interferogram of the HiReTT wing in ETW.

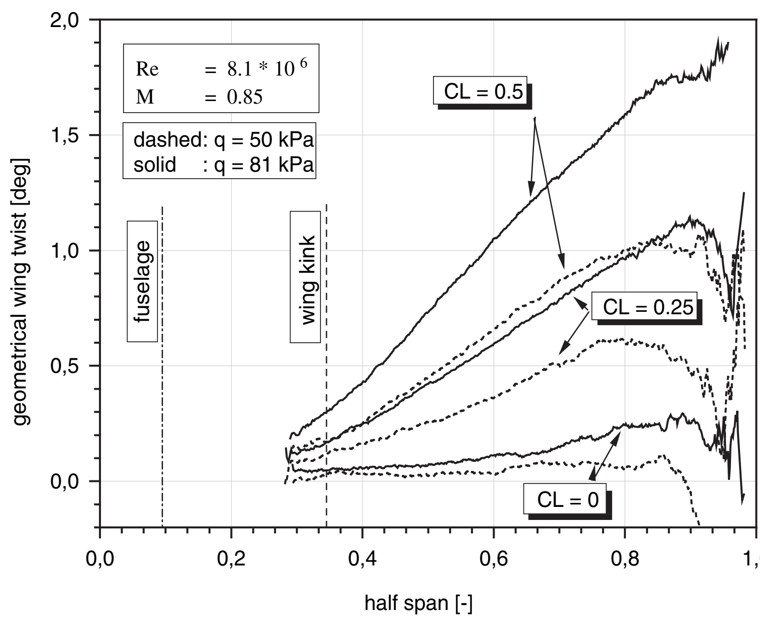


Figure 22: Effect of q-variation on wing twist of HiReTT model in ETW (c_L = lift level).

from the Moiré pattern. Furthermore, if the surface is deformed or shifted in z-direction (e.g. due to aerodynamic load), the change of the z-coordinates of the surface can be calculated by comparing both surfaces for the no-wind and the on-wind condition, yielding wing twist and bending.

In this case, the observation area of the Moiré system is about $0.60 \times 0.45\,m^2$ at an observation distance from 0.9 to 1.1 m from the top wall of the test section. The resolution is better than 0.05 mm for wing bending (z-direction) and better than 0.1° for twist.

Comparative measurements of the wing twist for different dynamic pressures q (caused by an increase in tunnel pressure) at a constant Reynolds number of 8.1 million (achieved at temperatures of 300 and 214 K, respectively) are given in Fig. 22.

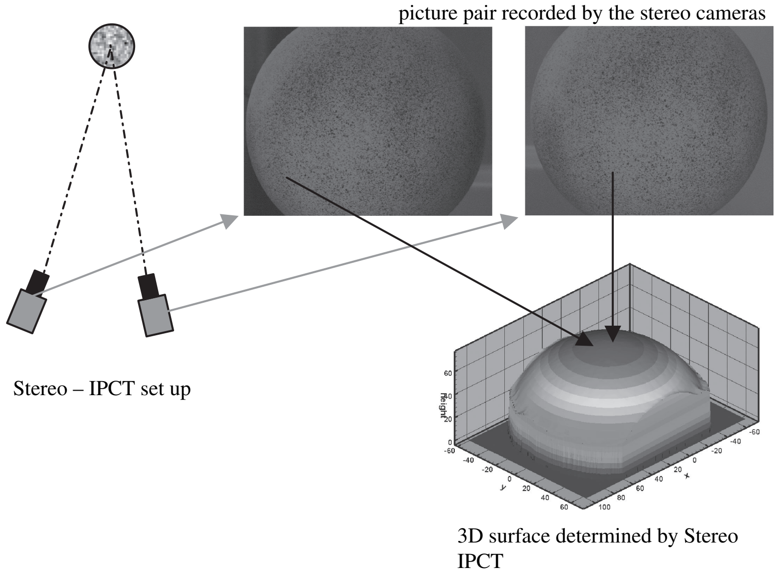


Figure 23: Stereoscopic IPCT and 3D surface determination.

Here, positive twist values represent a reduction in angle of attack. Reliable results have been gained between 30% and 90% span. Raising q by about 60% leads to growing twist levels amplified by the lift level c_L.

2.5.3 Image Pattern Correlation Technique

In contrast to the highly sensitive Moiré technique, IPCT is a robust general purpose method for measurement of model deformations utilizing standard equipment. A random dot pattern is attached to the model. A reference picture taken at rest is compared by means of cross-correlation techniques with a picture of the model under load to obtain the deformation. IPCT uses the same correlation algorithms as developed for PIV. The evaluation depends on the set-up.

Monoscopic camera set-up. A reference picture taken at rest is compared by means of cross-correlation techniques with a picture of the model under load to obtain the deformation. This set-up is appropriate especially for 2D deformations.

Stereoscopic camera set-up (Fig. 23, left). Stereo-IPCT yields the absolute 3D-surface calculated from the cross correlation between the pictures of two (or even more) cameras. Figure 23, left shows the surface determination considering as example a sphere with a radius of 80 mm. From the two pictures of the camera pair (Fig. 23, upper right) the absolute 3D-surface (Fig. 23, lower right) is calculated by means of cross-correlation. From the surface data points the parameters of a sphere equation are determined by optimization (Fig. 24, left). In this test case the calculated radius of the sphere is 79.96 mm. It corresponds to a deviation of 0.05% of the radius or 0.2 pixels (Fig. 24, right).

The deformation vector field is obtained by the correlations between the evaluated surfaces of different loads. In wind tunnel applications, these deformation vector fields are the base for wing bend and wing twist calculations.

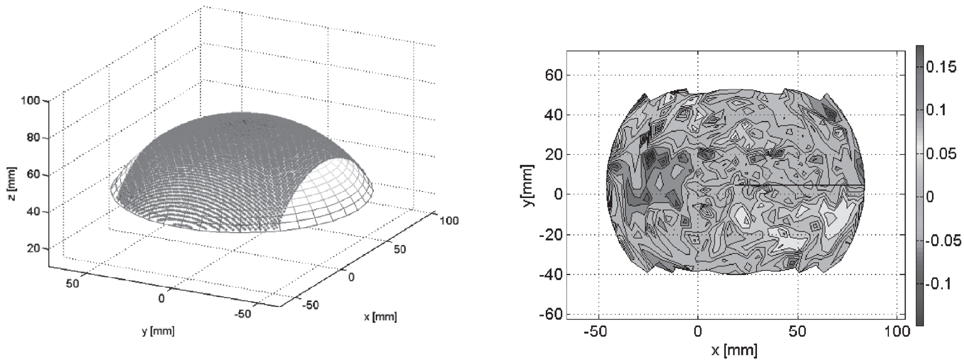


Figure 24: Left: Curve fitting of the measured surface points, red points—IPCT data points, mesh—optimized sphere. Right: Z-residuals plotted over $x-y$-plane. Standard deviation of the measured z-coordinates from optimised sphere = 0.045 mm.

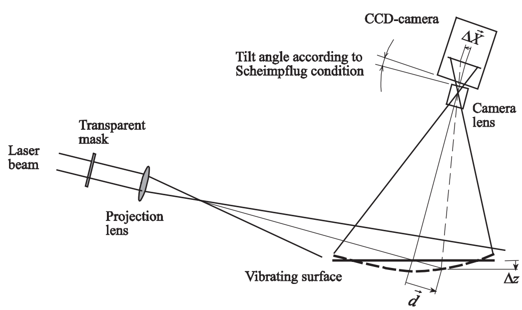


Figure 25: Experimental arrangement of the PROPAC method.

2.5.4 Projected Pattern Correlation technique

A dot pattern is projected onto the model. A reference picture taken at rest is compared by means of cross-correlation techniques with a picture of the model under load to obtain the deformation [8].

The experimental set-up of the PROPAC method can be seen in Fig. 25. A pattern of tiny bright spots is projected onto the model and will be observed by a camera in Scheimpflug arrangement.

Figure 26 shows how the dot pattern of an image taken at $t = t_1$ and $t = t_2$ will be cross-correlated. If the first image is taken at rest, the actual displacement will be obtained. If both measurements are taken in symmetric position with relation to the zero crossing of a vibrating structure (triggered recording), the surface velocity can be obtained.

Figure 27 shows the results of a vertically hanging honeycomb sandwich plate, vibrating at resonance frequencies of 63.6 and 115.9 Hz. The different vibration modes are clearly visible. They are characterized by superimposed sinusoidal deformations arising symmetrically to the horizontal and vertical central line of the plate.

All model deformation and location measurement methods mentioned above are under development for use in wind tunnels at present at DLR. The POSI, IPCT and PROPAC methods seem to be more robust and easier to handle in the environment of a wind tunnel, whereas the Moiré technique seems to have higher sensitivity (order of wavelength) as compared to the methods relying on cross-correlation evaluation, which are known for maximum accuracy of 1/10 pixel in

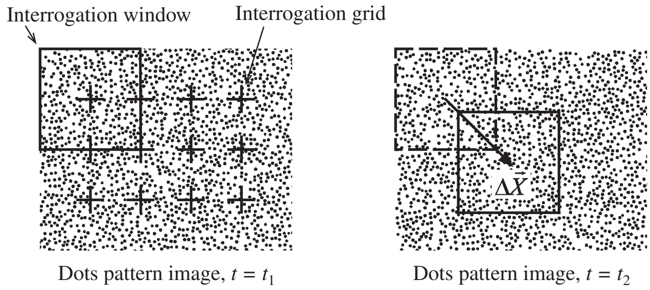


Figure 26: Correlation analysis of successively captured random dots pattern images.

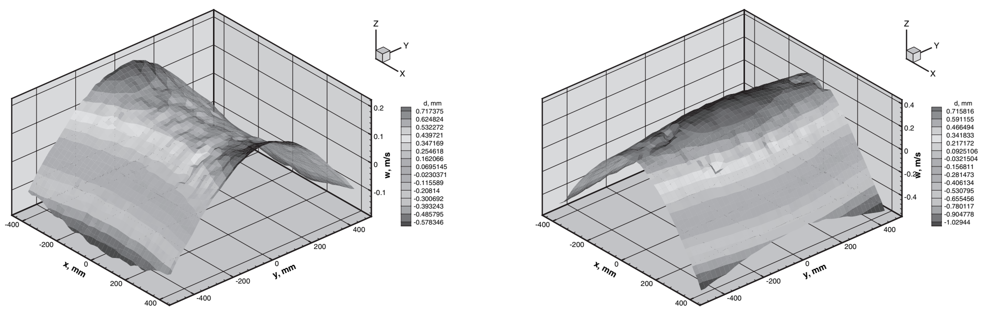


Figure 27: Surface velocities of a vibrating honeycomb sandwich plate excited at its resonance frequencies of 63.6 Hz (left) and 115.9 Hz (right). Scaling of *w*-axis is different.

the plane of CCD sensor, which has to be transformed into the real displacement with the magnification factor at imaging. A feasibility study performed during a flight test with an A340-400 Airbus plane has proven the robustness of the IPCT method also for applications outside the wind tunnel.

2.5.5 Potential of position and deformation measurement techniques for investigation of natural flows

All methods described here for the measurement of position and deformation of objects can be employed for flows in nature as well. They are all non-intrusive and do not influence the object under investigation. In case of living objects it should be tried to make use of natural patterns on the surface (skin) of, e.g. a fish or a butterfly.

3 Conclusions

It has been shown that image-based measurement techniques allow new insight in aerodynamic phenomena in complex unsteady flow fields. The quality of the data will enable detailed comparison with the results of numerical calculations in future. Most of the image-based techniques developed for application at objects of ‘industrial’ interest have been applied to flows in nature as well or can easily be applied as they are non-intrusive. In most cases the image-based methods can be scaled to the size of the object under inspection from micrometres to kilometres. When image-based methods require strong illumination, tracer particles, or paints to be applied to the surface of living objects care has to be taken these do not harm the living object or influence the measurement.

The development of image-based measurement techniques is mainly driven by the needs of industry. Industrial applications becoming more and more complex (moving and deforming objects, unsteady three-dimensional flow fields, etc.) the measurement techniques must be further developed. Thus it can be expected that in future well-developed measuring techniques ready for use in industrial applications will be available for use for flows in nature as well.

Acknowledgements

Many people have contributed to the results presented in this paper: previous and current colleagues from the Department of Experimental Methods, colleagues from international teams performing the tests with advanced measurement techniques and the teams from the large industrial wind tunnels where the tests have been carried out. Without their continuous strong support these results would not have been possible.

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