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PIV method, maintenance, exploitation and method finalization

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Abstract

PIV (Particle Image Velocimetry) method as a visual aspect of the fluid flow behavior, by itself is a continuous „problem“ as its exploitation is multi-layered and significantly negligible in comparison of the visualization shown. Namely, vector and point positioning are a direct matrix proportion which is delayed in comparison with the original disposition in accordance with the time passed in which the exploitation was performed.

Exploitation of „material“ is a severely significant factor in the maintenance process of critical systems as PIV (Particle Image velocimetry) systems.

In this paper, the maintenance process of a critical laser component is defined in context of retention of stable measurement of airflow behavior in a standard subsonic closed type wind tunnel.

The paper describes the procedure of maintenance of a mechatronic system which is used in PIV (Particle Image Velocimetry) method, independently in the aspect of the hardware components (energy, power) and in the aspect of the software-based system manipulation.

Key words

Particle Image Velocimetry

Exploitation

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1. Introduction

The subject of examination in aerodynamics is the laws of mutual correlation of fluids and the physical body that is moving in the fluid. Theoretical aerodynamics uses a complex mathematical apparatus to present and solve complex occurrences, where as experimental aerodynamics studies the real interaction of fluids and bodies of different shapes in free movement or in laboratory conditions, in surroundings such as aerodynamic tunnels.

Examinations in this area are very interesting and are part of a multidisciplinary domain of problematics which in order to be solved correctly, are in need to be supported with the integration of knowledge from different areas and aspects.

Basics fluids, which are used in experimental aerodynamics, such as air and water, are colorless fluids, where the fluid behavior cannot be directly evaluated, seen or filmed.

Thus, the need for distinct methods for such evaluations emerged. These distinct methods can be categorized in a specific research discipline as part of experimental aerodynamics and fluid visualization. They are a set of methods that use a modern approach of scientific and technological developments in order to make a representation of fluid behavior around aircraft models, projectiles and other objects in aerodynamic wind tunnels or other real aircraft and other objects in real conditions of flight or other exploitation means.

Other than, the before mentioned aerodynamic laboratories, which have the main focus of research of aircraft, these visualization methods can be successfully used in experimental approach to fluid behavior in different technical systems (such as – pipping of different geometries and dimensions), biological systems, fluid behavior in civil engineering (bridges, towers, traffic overpass, housing) and fluid behavior in transformational products (such as – trains, automobiles, boats)..

With the currently available software apparatus and digital rendering of images, it is possible to perform an automatic analysis of fluid visualization effects and to receive qualitative and quantitative values of fluid flow parametrization, which are not available in the classical and conventional measurement approaches.

The basic categorization of visualization methods is:

- Classical methods of fluid flow evaluation (indication based)
- Optical methods
- Special methods which are the combination of the above two

The area of use of these methods is in correlation with the basic partition of fluids on incompressible and compressible fluids, where the first methods were used for visualization of subsonic fluid flow (incompressible fluids), the second method is used for evaluation of supersonic fluid flow (compressible fluids), and the third is used for subsonic and hypersonic fluid flow area where the specific density of the fluid is lowered.

The first method was named the classical method, as the length of exploitation of these methods surpasses other approaches. Today, this group of methods includes the most modern technologies, lighting techniques, fluid flow imaging and processing.

The optical method includes the shadow methods, interferometric (classic and holographic) method and Laser Doppler Anemometry (LDA) which later evolved to Particle Image Velocimetry (PIV) method.

The group of special methods is classified as the combination of the before mentioned two.

2. PIV method

The evaluation and analysis of velocity vector components of microscopic fluid particles by quality imaging (Particle Image Velocimetry (PIV)) is a very important experimental technique in fluid mechanics and aerodynamics. The determination of fluid velocity is performed interactively via the velocity of captured particles, as it is implied that the particles in the fluid follow the actual fluid flow. The technique is based on the analysis of two consecutively captured images in a very short period of time t и Δt.

PIV is present more and more in the aerodynamic testing research, as it allows the evaluation of the complete fluid flow field in a relatively small time frame of a few μs, and provides information on non-stationary flows, which is very hard to procure with other experimental approaches. The most common light source in PIV is a Nd:yag laser, which operates in a dual-layer impulse regime with an approximate frequency of 10Hz, and impulse time frame of consecutive impulses of a couple of microseconds. Images are captured whenever the laser shutter is open, thus the CCD (Charged Coupled Device) camera or other camera types are positioned in a 90° order in relation to the laser-lit plane.

Image processing is conducted via a deliberately developed software packages, which use cross-correlation functions. Depending on the CCD camera used and particle concentration in fluid, the trajectory of particles is used or a correlation image processing is performed.

Also, a combination of the two proved to be a good approach in order to enhance the resolution of imaging.

3. Components of the PIV system and maintenance recommendations

3.1. Cameras

In order to perform PIV analysis of the fluid flow, two exposures of laser light were required at the exit of the camera. Initially, with the inability of the camera to capture multiple frames at high speeds, both exposures were shot on the same frame while a single frame was used to determine the flow rate. A process called autocorrelation was used for this analysis. However, as a result of autocorrelation, the direction of flow becomes unclear, because it is not clear which parts are from the first pulse and which are from the second pulse. Faster digital cameras using CCD or CMOS (Complementary Metal – Oxide – Semiconductor) chips have been developed to capture two frames at high speeds with several hundred ns frame differences. This allowed each exposure to be isolated on its own frame for a more accurate cross-correlation analysis.

Figure 1. PowerView HS-2000

The limitation of typical cameras is that this speed is limited to a couple of shots. This is because each pair of shots must be transferred to a computer before another pair of shots can be taken. Typical cameras can only take a couple of shots at much slower speeds. High speed CCD or CMOS cameras, which are much more expensive.

Camera maintenance is focused on monitoring lens wear due to mounting and dismounting on the cameras, where the damaged lens distorts the image due to scratches and thus enhances measurement error to the point where in some cases the images are not usable for processing. Preventive protection from the laser beam of the PIV device is also important - the user has to keep in mind that the laser mean does not hit the camera chip at an angle; even when it comes to a reflective beam,any exposure to the laser beam there can induce permanent damage to the camera chip.

3.2. Laser and optics

For macro-PIV settings, lasers are dominant because of their ability to produce high powers with short pulse durations. This gives a short time exposure for each frame. Nd: yag lasers, which are most commonly used in PIV settings, emit light, primarily at a wavelength of 1064 nm with its harmonics. For safety reasons, the laser emission is typically filtered to isolate 532 nm harmonics (this is the green light, the only harmonic that can be seen with the naked eye). An optical cable can be used to direct the laser light to the experimental setup.

Figure 2. Nano PIV Series

The optics consist of a spherical lens and a combination of cylindrical lenses. The cylindrical lens expands the laser into a plane while the spherical lenses compress the plane into a thin layer. This is critical because the PIV technique cannot generally measure movement normally on a laser curtain and is thus ideally eliminated by maintaining a fully two-dimensional laser curtain. It should be noted that spherical lenses cannot cut a laser curtain into a real two-dimensional plane. The minimum thickness is in the order of the wavelength of the laser light and takes place at a certain distance from the setting of the optics (focal point of the spherical lens). This is an ideal location for setting up an experiment analysis area. You also need to choose the right camera lenses to focus and visualize the particles within the research area.

Laser maintenance is mostly focused to monitoring the temperature of the laser by monitoring the parameters of the cooling system consisting of a water pump, fan, cooler, cooling block and other components for the distribution of fluid from the cooling system to the laser. Preventive maintenance includes removing dust from the cooling system filter as well as regular replacement of demineralized water in the cooling system. Although the water is demineralized, if it is not changed often, deposits appear on the walls of the system, which can affect the operation of the cooling system. Ignoring the mentioned items causes the laser to overheat, which can lead to permanent damage to the laser head. One of the problems that can occur when using PIV lasers in wind tunnels, is that due to vibrations from the operation of the wind tunnel; although micro vibrations, laser lenses move, so it is necessary to calibrate the laser from time to time to focus the laser beam.

3.3. Synchronizer

Standalone electronic synchronizers, called digital delay generators, offer a time variable of resolution from as much as 250 ps to a larger number of ms. With up to eight channels of synchronized time, they offer the means to control several lamps and Q-switches (variable pulse length), as well as for multiple camera exposures.

Figure 3. LaserPulse Synchronizer TSI

Synchronizer maintenance is based on fan maintenance and cleaning of the protective net and the cooling box filter. A preventive measure is also the maintenance of all connection ports; due to poor maintenance of the above, signal loss can occur and desynchronization of the opening of the covers of PIV lasers and cameras.

4. Principle of operation

The experimental set up of a PIV system is constructed from a number of sub-systems: the unit for fluid flow induction (such as – aerodynamic wind tunnel with its sub-systems: System for injecting cold gas and exhaust system for tunnel pressure regulation and control). Which require its own maintenance actions and safety precautions. In the majority of appliances, the tracking particles are added in the fluid flow. These particles have to be lit in the fluid flow plane at least two times in a short time interval. Light provided to the tracking particles are then captured via a high-quality objective either on a single camera or on a separate camera frame on a special CCD sensor.

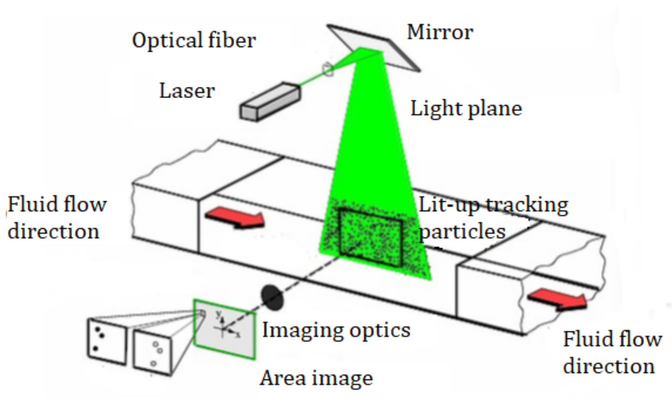

Figure 4. – Experimental PIV set-up

Local vector of movement of tracking particles of the first and second laser light sequence is provided for each part of plane area through a statistical method evaluation (Image 2). To decrease the amount of data that are being captured by PIV, it is necessary to perform complex post-processing. Because of this, photographic PIV captures are being digitalized after its development supported with scanners. The output of a CCD sensor is stored directly in real-time in the memory of the system PC (Personal Computer).

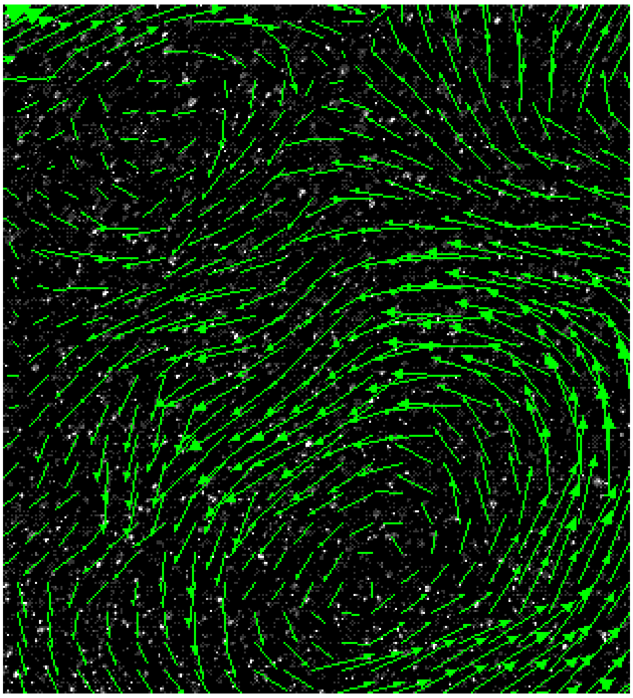

Figure 5. Vectors after PIV post-processing

To better understand the special technical resolution in the area of laser lighting it is needed to better understand some basic and overall aspect of the technique used:

Particle size of tracking: the need of using tracking particles to measure the velocity of fluid flow demands a careful evaluation of each experiment in order to determine if the tracking particles actually “follow” the fluid flow direction.

Lighting: in the application in gas flow evaluation, it is mandatory to have a light source of great power, in such way that the light is scattered by the tracking particles so that the photographic system is cable to differentiate the tracking particles.

Shutter duration of light impulse: the duration of the light impulse has to be short enough, so that the particle movement is in “freeze” while exposing it to the light impulse in order to avoid picture quality degradation.

Time delay in between two light impulses: the delay between two light impulses has to be long enough to allow the tracking particles to change location between two image captures and short enough to avoid the exit of tracking particles in the lit-up plane.

5. Evaluation of the velocity field

If the positioning vector marked as X_i and the vector of tracking particle marked x_i in the first image exposition, are connected with the following relation:

$$X_i = x_i \, \mathrm{M},$$

where the factor M is a magnification factor.

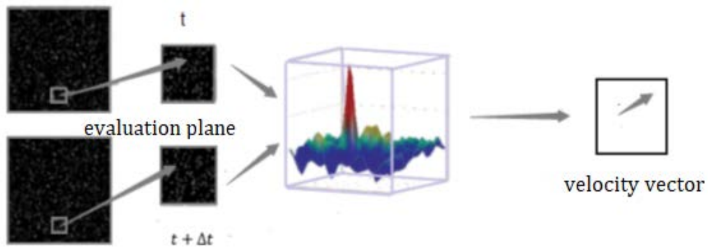

Figure 6.

Field intensity of the first exposition image is then defined with the following relation:

$$I_{(X)} = \sum_{i=1}^{N} V_0(X_i)\tau(x - x_i)$$

where $V_0(X_i)$ is the function of transfer which gives the lighting energy of the image for a separate tracking particle and inclusive interval volume and its conversion into a electronic signal, τ(x) is a function of a scattered point of the image capturing objective. Under the assumption that between two expositions all particles inside the lit-up plane of evaluation are moving with the same time shift ΔX_i, the intensity field of the second exposition image can be defined in the following relation:

$$I_{(X)} = \sum_{i=1}^{N} V_0(X_j + \Delta X)\tau(x - x_i - \delta x),$$

where δx is a substittution of the image of particle and can be approximated with the following relation: $\Delta X = \delta x / \mathrm{M}$.

The velocity field is then calculated using cross-correlation functions:

$$R_{(s)} = \int I_1 x I_2 \ x + s d_x,$$

where:

- $I_1 and I_2$is the evaluation plane
- $x$is the location of evaluation
- sis the shift between two images

$$R_{(s)} = R_{c(s)} + R_{F(s)} + R_{D(s)},$$

Where a cross-correlation is most commonly derived from a Fourier transform equation.

For a quantitative interpretation, it is more desirable to use a small concentration of a great number of small particles to track the fluid flow. The received "negative" (photogram), which is consisted from a great number of tracking particle images under optical magnification, is then evaluated partition by partition. Such digitalized output is often consisted of 256x256 elements, in a hardware processing, 512x512 or 1024x1024 elements.

In further processing, original particles should be targeted. Having in mind that the shutter time between two impulses is known, and the distance between tracking particles is known to be evaluated using an algorithm of digital image processing, the velocity is then calculated through the following equation:

$$\bar{V} = \frac{M_d}{t},$$

where:

- $\bar{V}$ – velocity vector of field
- M – optical magnification
- d –image shift vector of tracking particles
- t- shutter time between two laser impulses.

For image processing Young interference apparatus, correlation of space and direct extraction of images is used.

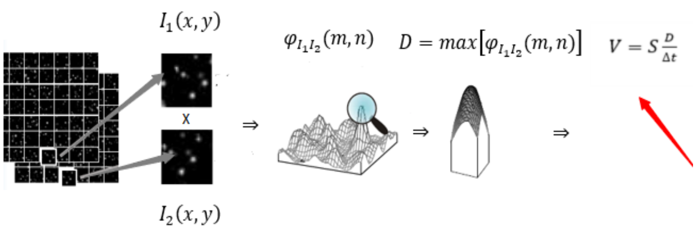

Figure 7. Evaluation of plane velocity

6. Analysis of results

Images obtained by the PIV method are analyzed by dividing into several regions of the study area. It is then possible to calculate the displacement vector for each region using signal processing and autocorrelation or cross-correlation techniques. This is converted into speed using the time between laser shots and the physical size of each pixel on the camera. The size of the test window should be chosen so that there are at least 6 particles per window on average.

The synchronizer controls the time span between image exposures and also allows image pairs to be obtained at different times along the flow. For accurate PIV analysis, it is ideal that the flow region of interest should show an average particle change of about 8 pixels. This is a trade-off between a longer time intervals that would allow particles to travel further between frames, making it difficult to determine the region of the test, which could lead to too difficult identification of scattering within the flow.

The scattered light from each particle should be in the range of 2 to 4 pixels in the image. If too large an area is captured, the particle image size decreases and a lock may occur with loss of sub-pixel accuracy.

7. Conclusion

PIV (Particle Image Velocimetry) is one of the modern methods of measuring particle fluid flows and their visualization; as such, PIV is a big step forward in this type of measurement in wind tunnels, so it is extremely important to maintain proper and preventive maintenance to avoid damage to key components of the PIV system. The paper presents one of the ways of preventive maintenance of the system as well as observations on possible problems that can occur due to the actual exploitation of the system in wind tunnel surroundings. It is shown that preventive maintenance can greatly extend the life of the system and maintain the constant operation and precision of the system required for this type of measurement in wind tunnels.

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