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Velocity measurement of compressible air flows utilizing a high-speed video camera

M. Raffel, J. Kompenhans, B. Stasicki, B. Bretthauer, G. E. A. Meier

Abstract PIV-measurements of the flow above a pitching airfoil were conducted in a transonic wind tunnel. An ultra high-speed video camera was used for separate recording of two exposures. The data was analysed using the cross-correlation method. The results show the applicability of the technique in high speed flows.

1 Introduction

Particle image velocimetry (PIV) is applied with growing success to an increasing wide variety of flows. The most important step towards adapting this technique to different applications was the development and use of the image shifting technique as described by Adrian (1986), Lourenço (1988) and Grant et al. (1988). This technique eliminates directional ambiguity, and also allows a free selection of the pulse separation in spite of possible restrictions in the utilized evaluation methods. Furthermore, if the two necessary exposures are recorded on the same film or video chip, this technique helps to avoid an overlap of particle images in regions of lower flow velocities. Free choice of the pulse separation means that this measuring method offers excellent metrological and spatial resolutions, as well as a higher tolerance towards out-of-plane flow components and large velocity gradients. This makes it highly adaptable to a wide variety of conditions.

The same advantages can be achieved by recording the different exposures on separate images. However, the use of a video camera, which is dependent on the video rate, gives rise to new time restrictions as reported by Willert and Gharib (1991) and Merzkirch et al. (1994). The use of a high-speed video camera has been suggested by Cho (1989) as a possibility for circumventing those restrictions. This article explains which devices and procedures can best be used to perform this kind of measurement in high-speed applications. The attainable quality is demonstrated by showing a result of a current measurement.

2 Description of experiment

The unsteady flow field above a NACA 23012 airfoil oscillating in pitch (oscillation frequency $f_0 = 10$ Hz) was investigated in a wind tunnel by means of particle image velocimetry. The short measuring time of only a few microseconds required for PIV allowed measurement of the instantaneous flow fields. This dynamic stall investigations were performed in the high speed-blow down wind tunnel (HKG) of DLR Göttingen. The free-stream Mach number was $Ma_\infty = 0.3$, while the angle of incidence varied from $\alpha = 11^\circ$ to $\alpha = 25^\circ$. Due to the limited repetition rate of our Nd:YAG laser (10 double pulses per second) it was not possible to acquire 8 consecutive images which could be evaluated by performing the cross-correlation technique between each two following images. Therefore in this case four image pairs were recorded, which were treated as four single measurements. The synchronisation between illumination and motion of the model was performed by two independent high-precision pulse generators which controlled the airfoil oscillation and the pulse laser. The observation distance was $d_0 = 2$m and the focal length of the imaging lens $f_1 = 150$ mm. The aim of the investigation was to observe the flow area above the leading edge of the airfoil at velocities ranging from 70 m/s up to 180 m/s.

3 Ultra high-speed video camera UHSV-288

The ultra high-speed video camera UHSV-288 was developed by Stasicki and Meier (1992) at DLR Göttingen primarily for the purposes of making video recordings of very fast processes, especially of unsteady flows. The UHSV-288 is a PC-supported system allowing manual selection of exposure times going down to 0.6 µs and exposure intervals with a resolution of 50 ns, resulting in a theoretical framing rate of over one million images per second. The system delivers a sequence of up to 8 pictures with an image resolution of 512×256 pixels with 256 grey levels. The object to be registered is projected onto 8 CCD sensors (two of them are shown in Fig. 1) by means of a beam-splitting mirror, located directly behind the camera lens. Due to the high responsivity of the used CCD sensors the sensitivity of the UHSV-288 camera is that of a photographic camera using a fast film, even if each CCD sensor is only illuminated by 1/8th of the incident light intensity. The series of time-staggered images is created by the sequential release of freely triggerable electronic shutters. The images are stored on 8 frame grabber cards located in an industrial standard PC, and are accessed as bitmap files. An enhanced system with an image resolution of 752×291 pixels is manufactured under licence by the Cordin Company/U.S.A.

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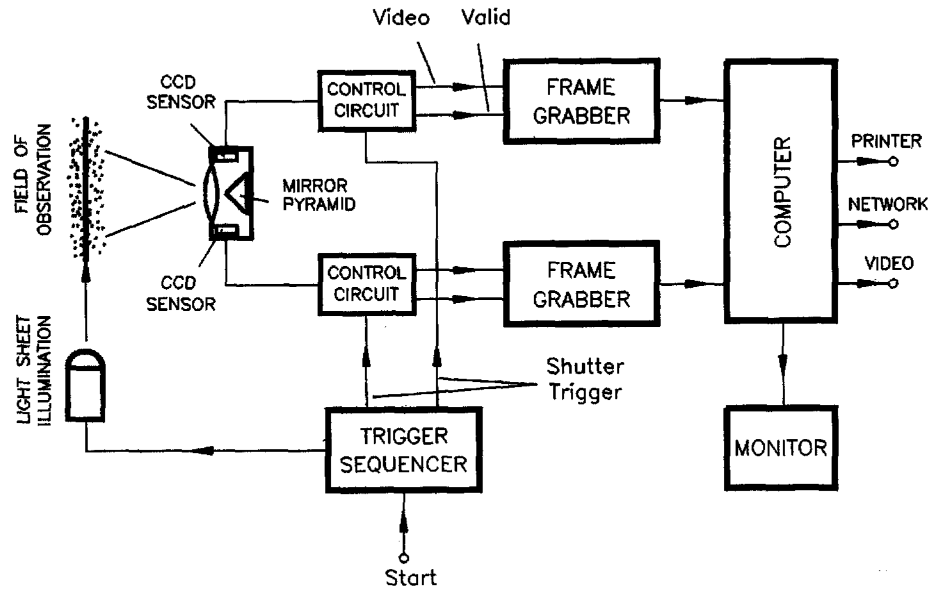

Fig. 1. Block diagram of the UHSV-288 (only two channels shown)

4
Data extraction

The PIV evaluation system of the DLR is based on SCIL Image, an image processing system developed by the University of Amsterdam. DLR has developed a number of modules for PIV evaluation using optical Fourier processors. These modules were designed in such a way that they can now be applied in the cross-correlation method without requiring any major modifications. The following procedure corresponds in all main points to methods that have already been described in detail by Willert and Gharib (1991) and Keane and Adrian (1992).

A small window, e.g. 32×32 pixels, is extracted from the first image. A window of the same size is taken from the second image, with a position which deviates from the first by $(\Delta x, \Delta y)$. This deviation is defined by the user and corresponds to the expected particle image displacement. If the displacement is not known, it can be defined using the auto-correlation of the sum of both images in a larger sampling window. The Fourier transformation for both windows is then calculated. A complex conjugate multiplication is performed between the two transformations. This results in a cross-power spectrum which can be inversely transformed to yield the cross correlation function. The highest peak in the cross-correlation function and its geometrical location (centre of gravity) is then determined taking into account that the peak was displaced by $(-\Delta x, -\Delta y)$. This procedure is repeated for sampling windows overlapping 50% throughout the image. The cross-correlation technique has two advantages over autocorrelation techniques: The size and sign of the velocity vectors can be uniquely recovered, and a flow can be evaluated even when the particle displacement is greater than the evaluation window or smaller than the particle image diameter. In addition, the size of the evaluation window can be adjusted to cope with the problem of different structures present in the flow. By contrast, the auto-correlation technique only produces results if the particle displacement is significantly smaller than the evaluation window, and if the particle images do not overlap in areas of low flow velocity. These restrictions make it necessary to apply image shifting techniques, which are no longer necessary with the help of the cross-correlation technique and of separate recording of both exposures.

5
Experimental result

The investigation shows the strong unsteady behaviour of the flow field above the airfoil, noticeable in the downstroke motion, and thus allows new insights into the flow phenomena. Measurements were taken with the same experimental facility using DLR Göttingen's conventional PIV system. This system consists of a photographic camera, a mechanical image shifting system and an evaluation unit which is based on the Young's fringes method. It is usually used for wind tunnel measurements in low and high speed flows. Due to the lower resolution of the video camera, a significantly smaller observation field of approximately 10×10 cm^2 had to be selected, contrasting to an observation field of approximately 20×30 cm^2 for the case of the photographically acquired images as described by Kompenhans and Raffel (1993). But even with this reduced size of the observation field the same spatial resolution can not be obtained. According to Prasad et al. 1992 the pixel size should be in the order of half the particle image diameter, which is approximately 20 μm at the described recording conditions (Kompenhans and Raffel 1993). The video system can fulfil this requirement in horizontal direction (10.7 μm effective pixel size) but can not fulfil this requirement in vertical direction (22.2 μm effective pixel size) due to the reduced resolution of the CCD sensor in vertical direction. This leads to a reduced accuracy of the data as obtained with the video system (especially in vertical direction) in contrast to the data as obtained with the photographic PIV system.

The details of the flow field observed are nevertheless satisfactory when using the high-speed video camera in conjunction with the cross-correlation technique, and operation is considerably easier. As an example of PIV recording by means of the UHSV 288 video system Fig. 2 shows the dynamic stall vortex

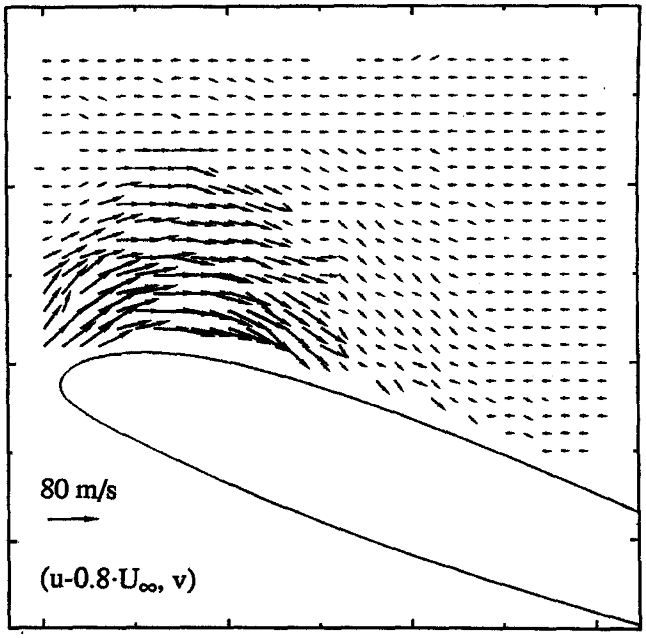

Fig. 2. Instantaneous flow field above the leading edge of a NACA 23012 airfoil in pitching motion ($Ma_\infty = 0.3$, $f_0 = 10$ Hz, $\alpha = 20°$>).

in the stadium of initiation at an angle of incidence of 20° during the upstroke motion.

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Reynolds number dependence of the drag coefficient for laminar flow through electrically-heated photoetched screens

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Abstract Experiments are performed to measure the drag coefficient of electrically-heated screens. Square-pattern 80 mesh and 100 mesh screens of 50.8 μm-wide wires photoetched from 50.8 μm thick Inconel sheets are examined. Ambient air is passed through these screens at upstream velocities yielding wire-width Reynolds numbers from 2 to 35, and electrical current is passed through the screens to generate heat fluxes from 0 to 0.17 MW/m^2, based on the total screen area. The dependence of the drag coefficient on Reynolds number and heat flux is determined for these two screens by measuring pressure drops across the screens for a variety of conditions in these ranges. In all cases, heating is found to increase the drag coefficient above the unheated value.
A correlation relating the heated drag coefficient to the unheated drag coefficient is developed based on the idea that the main effect of heating at these levels is to modify the Reynolds number through modifying the viscosity. This correlation is seen to reproduce the experimental results closely.

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