An instantaneous method for real-time velocity vector display in flows

B. Ruck

Institut für Hydromechanik, Universität Karlsruhe, Forschungsgruppe Strömungsmeßtechnik, Kaiserstr. 12, 76128 Karlsruhe, Germany

Received for publication 16 December 1996

If we consider experimental methods in fluid mechanics as they are used in practice, there is a strong need for fast visual flow information, e.g. velocity vector display. Existing "whole field" techniques can also deliver velocity vectors (beside other quantities), however, the main restraint with these techniques is the relatively long frame processing time, which usually does not allow to extract continuously real-time information from the flow. Therefore, flow fields can often not be visualised with a sufficient time resolution. The present paper describes a new technique for the real-time display of velocity vectors in flow fields. With the new technique, real-time analyses of flows can be performed quickly with an incomparably high time resolution. The achievable time resolution no longer depends on image processing times.

Keywords: real-time velocity vectorisation; particle tracking anemometry; velocity vectors; flow vectors; flow field display

1. Introduction

So-called whole field measuring techniques have been developed to analyse flow velocity fields instantaneously. Among these flow measuring techniques, particle tracking anemometry (PTA) [1, 2] and particle image velocimetry (PIV) [3-5] are preferably used. Basically, these techniques were conceived to obtain both visual vector plot display and data sets. To achieve (only) images of velocity vectors, which is often sufficient for industrial practical flow analyses, the use of such techniques is coupled with relatively long image processing times [6]. The latter is due to the fact that velocity plots usually display the final results of a PTA or PIV computational procedure. The use of Digital Particle Image Velocimetry [7] improves the speed of processing significantly, however, it does not fundamentally eliminate the time mismatch between e.g. real turbulent frequencies in the flow under consideration and maximum obtainable processed frame frequencies. At the moment, existing whole field techniques cannot be used in real-time neither to display velocity vectors nor to deliver data sets of turbulent flows. This limitation started the term "virtual real-time", which is most misleading.

To obtain velocity vector plots, the time needed for the vectorisation of one whole field measurement with existing methods basically consists of the sum of times needed for the computation of the velocity and direction information in all interrogation areas of an image or frame. With single frame technique, the direction of the velocity vectors in a field can only be extracted by an additional coding procedure, which has to be applied during the exposure time of the image detector or film. Sophisticated methods have been proposed using single or multiple pulsed decoding [8-10]. Color-coding was used in PTA [11] and in PIV, a mechanical solution to measure the flow direction was based on mirror shifting [12]. Nowadays cross-correlation cameras are used for directional decoding.

Summarising all these different approaches reveals that time is needed for the computation of each vector field, which limits the frame rate and allows the conclusion that existing whole field measuring techniques are not suitable as providers for continuous real-time velocity vector displays in technically relevant turbulent flows. The latter can be demonstrated with the following example.

Suppose we want to visualise in a vectorised form 10 s of a turbulent flow in a 2-d laser light sheet. Let the characteristic turbulent frequency be in a realistic range of about 10 kHz. Then, for satisfactory time resolution, the rate of frames needs to be in the same order of magnitude resulting in at least 10^4 frames for the 10 s period. Multiplying this number by the processing time for one frame gives the total time needed to vectorise the flow field over 10 s without losing relevant turbulent information. However, relying on existing whole field measuring techniques like PTA or PIV with film-based interrogation spot processing and a typical single frame processing time of about 10 min on a workstation, this will last about 70 days! It is apparent that even a reduction of a factor 10-100 as it is attainable nowadays with the latest developments in video-based PIV-systems (so called "virtual
real-time' systems) will not fundamentally eliminate this time problem.

To obtain velocity vectors in a much faster way, a new approach is described, which reduces the processing time for quantitative flow field vectorisation to zero and, thus, solves the time-mismatch between data acquisition and velocity vector display with the existing methods.

The new technique is based on an instantaneous analogue imaging process, which uncouples the field vectorisation from any processing time and allows to convert particle traces into vectors during the detection. Thus, real-time velocity vector analyses of turbulent flows can be performed with an uncomparably high time resolution.

2. Physical background

To understand the physical background, it is worthwhile to consider the imaging of a point by a lens. Suppose we image an illuminated point or spot of defined diameter with a lens and a magnification factor of one onto a detector plane with given sensitivity (film, CCD). Because of diffraction and aberrations, the spot diameter in the image plane will not persist. Instead, a spot with almost Gaussian-shaped intensity distribution will result. In a 'perfect' diffraction-limited optical system without aberrations the resulting irradiance distribution in the image plane would correspond in shape to the diffraction pattern of a point source in the object plane. In optics, this phenomenon

Figure 1 Imaging points of different brightness and resulting diameters

Figure 2 Images of an illuminated spot with increasing intensity (top left to bottom right) detected with a CCD image sensor
is known as point spread and described by a point spread function. However, the visibility of the spot diameter in the image plane strongly depends on the choice or combination of the point illuminating power and the detector sensitivity. Increasing the illumination of the spot or the sensitivity of the image detector will result in increasing diameters in the image plane, see Figure 1.

In Figure 2 an image of illuminated spots is shown. As can be inferred, the spot diameter increases on the CCD image detector with increasing light intensity (increasing intensity from top left to bottom right).

This phenomenon can be used to vary the thickness of particle traces during the detection process. Thus, by an adequate modulation of the light intensity, traces of particles propagating in a laser light sheet or inside an illuminated volume can be converted into vectors during the detection without any processing time. Using e.g. high speed photography, this new technique allows to track turbulent flows instantaneously with a sufficient high time resolution. In Figure 3, a photograph of a simulated particle trace vectorised with the new technique is shown. The trace was generated by an illuminated particle mounted onto a rotating disk and videographed by a conventional CCD-detector, see also Figure 10. In Figure 4, the new principle for instantaneous vectorisation is realised by using a Bragg cell as a light intensity modulator. As can be inferred from Figure 4, the Bragg cell driver signal is a chain of pulses, each consisting of an adequate e.g. 40 MHz frequency sequence amplitude-modulated with an envelope showing a shape like an arrow. Due to the aforementioned relation between spot/trace thickness and illumination intensity, this specific driver signal converts streaks into vectors during the detection with conventional image detectors. However, there must be a synchronisation between the image detector and the driver pulse generating electronics. Without synchronisation, the image detection can be fragmental, yielding only parts of the vectors.

The synchronisation needs not be identical for the image detection and driver pulse generation. The system also works properly as long as the synchronisation rate for the driver pulse generation is an integer multiple of the synchronisation rate of the image detection. In this case the same particle is several times detected on the same frame yielding a number of vectors, which very easily allows to track particle movements. Figure 5 shows a real-time vectorised image (40 mm×40 mm) consisting of particle traces in a low turbulent water flow field. The image was detected with an exposure time of 1/50 s. The mean particle velocity can be obtained by dividing the trace length
by the exposure time and is about 1 m/s in Figure 5. In Figure 6, a real-time vectorised image with higher particle velocity is shown. The mean velocity in this case is about 20 m/s resulting from a trace length of about 20 mm and an exposure time of 1/1000 s.

In the case of sequential image recording, it should be stressed once again that the only time limitation with this new technique is the time needed to capture and store the already real-time vectorised frames. Frame rates in the range of $10^4$ Hz are nowadays feasible with high speed video technique (based on dynamic random access memory technique). Because of the fact that with the new technique vectorised frame rates of this order of magnitude can be obtained, this new technique is particularly useful to track turbulent flows without losing relevant information.

In Figure 7, partial images from different flow investigations are shown, underlining that this technique can be applied in a variety of flow regimes, i.e. from laminar and unidirectional to turbulent and rotational flows.

As far as the comparison to standard PIV or standard PTA is concerned, the new technique is first of all a method to display velocity vectors in flow fields. To assess its worth, it makes sense to compare the
Real-time velocity vector display in flows

Figure 7 Examples of vectorised particle traces from different flow investigations

Technique with other techniques which can deliver the same information, e.g. velocity vector displays. However, the comparison should be limited only to the capability of delivering velocity vectors, since it is well known and recognised that e.g. PIV-systems deliver further data field information.

Further quantitative technical information of the new technique cannot be given in general, since it depends on the specific application of the user. From the application of streak photography, PTA or PIV we know e.g. that exposure times of the camera have to be adapted to the velocity range expected. The main parameters of influence are also spatial resolution of the image detector, turbulent frequency and frame rate. All quantities have to be considered and matched yielding an optimum real-time vectorised image. It should not be a problem to display velocity vectors with this method via exposure time controlling from mm/s to hundreds of m/s, however, the problem is the simultaneous display of different velocity ranges in a single frame. Usually, the latter is described by indicating the dynamic range of the principle. The dynamic range, however, is a limiting factor with existing whole field techniques based on interrogation spot processing. Since the new technique for instantaneous real-time velocity vector display is not based on interrogation spot processing, i.e. a subdivision of the frame, the dynamic range is up to two orders of magnitude higher.

The new technique can be realised by modulating the intensity or transmission either at the light emission or at the detection side of a PTA-system. Alternatively, to the aforementioned Bragg cell version, mechanical versions using a chopper disc with a slit equipped with filters of appropriately chosen transmission factors were used as a light modulator too. In Figure 8, a chopper wheel rotates through a laser beam and the transmission characteristic of the filter combination shows a vector-like shape. This can be used to modulate the illumination of a light sheet or light volume, which in turn, leads again to vector-like particle traces on the image detector plane. However, electronic realisations of this principle are much easier to control, see also Figure 9, where the detector sensitivity is modulated directly.

The new technique can be built up as a stand-alone system for pure vector field visualisation or it can be combined advantageously with a PIV-like later-digitising process. In the last case, the grabbed online vectorised image has to be digitised and processed in a computer yielding the local amount and direction of the vectors as data field. If done so, the delivered information does not differ from that of standard PIV. However, one essential advantage of the new technique remains also in this case, because it allows the experimenter to step quickly through the recorded images by visual control and start the time consuming data processing only for the really interesting image sequences. In standard PIV, everything must be computed before gaining visual control of the flow at all.

Figure 8 Chopper version with filter combination and vector-like transmission characteristic
A problem associated with most whole field measuring techniques is that sometimes traces in a field are imaged fragmentally, which is due to the fact that particles do not reside during the full exposure time inside the illuminated light sheet or volume. For the visual impression and the quantitative visualisation, fragmental traces usually do not play any significant role, however, for an exact quantitative data extraction e.g. via the aforementioned data processing, fragmental traces can lead to a bias in velocity determination, yielding slightly smaller values. To avoid this phenomenon, the described real-time vectorisation technique can also be used for marking the particle trace shortly at the beginning of the image detection. Thus, a start mark will result and in a later-digitising process, traces of particles with correct start coding and vector head can be discriminated from those not showing these characteristics.

Detailed studies had been carried out concerning the possibilities to vary the vector shape with respect to the size of vector-shaft and vector-head. In Figure 10, the experimental set-up based on a Bragg cell as light modulator is given. Instead of real particles, a thin wire simulated a particle passing through the light sheet. Thus, reproducible 'particle' traces could be realised, see also Figure 3. A modulator electronics was developed, which allows to modulate the amplitude of the Bragg cell driving frequency in a characteristic vector-like manner. The shape of the envelope of the Bragg cell driving pulses can now be varied in a wide range, so that vectors of different shape can be generated easily. In Figure 11, a description of the features of the vectors changeable by the electronics is given. Basically the shaft length and the length of the vector-head can be manipulated and adapted e.g. to the exposure time of the image sensor or to the velocity range detected.

In Figure 12, variations of the ratio vector-head to vector-shaft are given. As can be inferred, the vector-head can be varied in length in a wide range. In fact, the whole vector can be represented only by a vector-head without any shaft. On the other hand, the vector-head can be reduced to a point as well. Generally, the curve in Figure 11 representing the

Figure 9 Real-time vectorisation of particle traces with the aid of sensitivity-modulated image sensors

Figure 10 Experimental set-up to generate reproducible velocity vectors in a light sheet
vector shape can be defined freely. Thus, realising only start and stop points allows to implement PIV-measurements with the same system used before with the real-time velocity vector display.

3. Conclusions

A new technique for the visualisation of flow fields was presented. This technique, which is based on an analogue vectorisation procedure, allows to display flow vectors in an illuminated light sheet or volume instantaneously. When compared to existing velocity vector display techniques, the new technique practically needs no time for the vector field computation. Thus, this technique is most suitable in turbulent research, where flow visualisations of high spatial resolution, i.e. high frame rates, are needed to analyse the phenomenology of the flow. Existing techniques with frame rates of about 5/s are not suitable for this purpose. When combined with a later digitising process, the new technique can also deliver data fields such as, e.g. standard PIV-systems.

Acknowledgements

The author would like to express his thanks to Mr Daniel Metz, who helped to perform the experiments and to Mrs Dietlind Bring, who helped to finalise this publication.

References

11 Wung, T.-S. and Tseng, F.-G., A color-coded particle