VKI Lecture Series – Post-Processing of Numerical and Experimental Data
Rhode St Genèse, Belgium - 11-15 February 2008

OPTICAL TECHNIQUES FOR VELOCITY MEASUREMENTS

A. BOUTIER

Office National d'Etudes et de Recherches Aérospatiales
BP 72, 92322 - Châtillon Cedex, France
Phone: 33 1 46 73 40 06 – e-mail: alain.boutier@onera.fr

SUMMARY

To measure one velocity component, the four different optical set-ups deduced from the theory of the Doppler effect are described; the most widely used "fringe" LV is more detailed: signal to noise ratio evaluation, velocity sign determination, general structure of the emitting and receiving optics, signal processors.
It exists different ways to process the signals issued from the detectors which receive the light modulated by the particles crossing the probe volume, in order to extract their instantaneous frequencies. Typically two main categories of signal processors can be distinguished: those working in the time domain (period measurement, and autocorrelators), and those working in the frequency domain (performing Fast Fourier Transforms). Some other exotic techniques are also reviewed.
Progressively two velocity components were simultaneously measured (for 2D flow investigations), and nowadays the local velocity vector can be obtained, which is of peculiar interest in 3D complex flows.
The great variety of systems able to provide three velocity components simultaneously is reviewed; among these set-ups, the most operational 3D LV is based on a probe volume formed by three fringe patterns, with different directions in space and with three colors. Nevertheless, this optimal concept of a 3D LV may lead to several mechanical and optical structures, the merits of which are discussed.
The basic principles of the other velocimeters used in fluid mechanics are also described. They concern either local measurements with the L2F or mosaic velocimeters, or more global and now more widely used techniques able to provide planar velocity information such as Particle Image Velocimetry (PIV) or Doppler Global Velocimetry (DGV)

1. INTRODUCTION

The starting idea of laser velocimetry has been that a moving particle changes the frequency of the incoming light due to the Doppler effect, so that the particle velocity can be deduced from this light frequency shift. We shall recall the theory and apply it to the optical waves; in fact their frequencies are so high that special optical devices, which are studied below, had to be designed in order to extract the velocity information.

Then, having shown that one velocity component is determined by this way, we describe the different means to measure the local instantaneous velocity vector. All these items are developed in paragraphs 2 to 10. The following paragraphs are dedicated to the following techniques:
- § 11: transit time velocimeters (L2F and mosaic)
- § 12: PIV
- § 13: DGV

2. BASIC IDEA: DOPPLER EFFECT

2.1 The dual Doppler effect

We assume that the illumination source is a laser: we shall justify this choice later when discussing the formulas. The laser beam (emitting an optical frequency f0) as well as the observer (which will be a photodetector) is stationary in the laboratory coordinates.

In a first step the moving particle is a mobile observer relative to the stationary laser beam source: due to the Doppler effect it receives a frequency f_p slightly different from f_0.

In a second step the moving particle, which thus is a mobile source, emits the frequency f_p towards the stationary observer which receives another frequency f due to a second Doppler effect. We are going to compute f as a function of f_0, the velocity vector $\vec{V}$ and the geometry of the system defined by two unit vectors: $\vec{r}_0$ along the laser beam and $\vec{r}_d$ along the observation direction.

<u>Stationary source; mobile observer</u>

A laser beam of frequency f_0 in vacuum propagates along a unit vector $\vec{r}_0$ in a medium having a refraction index n. The wavelength in the medium is:

$$\lambda = \lambda_0 / n = c / n f_0$$

c is the speed of light ($c = 3.10^8$ m/s)

Let $T_0 = f_0^{-1}$ be the period of radiation in vacuum; the wavelength $\lambda = cT_0/n$ represents the distance between two successive wavefronts O_1O_2. At the initial instant t_1 the particle (mobile observer) is at O_1 and meets a wave 1 emitted by the source. Then the particle moves at a velocity $\vec{V}$ to meet the next wave 2 at instant t_2 (cf. Figure 1). Then it comes with algebraic conventions:

distance traveled by wave 2 during $t_2 - t_1$ at velocity c/n along $\vec{r}_0$	=	O_1O_2	+	projection on $\vec{r}_0$ of the distance traveled by the particle during $t_2 - t_1$ at velocity $\vec{V}$

$$(t_2 - t_1)\, c/n \quad = \quad T_0\, c/n \quad + \quad (t_2 - t_1)\,(\vec{V} . \vec{r}_0)$$