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Flow characterization using a laser Doppler vibrometer

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Abstract

This paper shows how a scanning laser Doppler vibrometer (LDV), an instrument designed to measure vibrations of structures or objects, can be used in a non-traditional fashion to measure the flow around a cylinder. In particular the von Karmann vortex street which appears in the cylinder wake will be visualized. This is achieved by measuring the changes in the optical path induced by local fluctuation of air refraction index to which the laser vibrometer is sensitive.

The measurements obtained with the LDV will be compared visually to measurements done with particle image velocimetry and also with CFD computations for one test case. The specific frequency of the Von Karmann street predicted by the vibrometer, will be compared numerically to the other techniques for two different sized cylinders at three different velocities.

Keywords: Laser Doppler vibrometer; Flow characterization; Computational fluid dynamics; Particle image velocimetry

1. Introduction

Measuring physical phenomena in most cases means perturbing that exact phenomenon. This is no different in the fluid dynamic world. Measurement techniques are ever evolving minimizing the interaction between measurement equipment and the physical event itself [1,2]. In the fluid dynamic world this started out with relatively simple devices such as the constant temperature anemometer (CTA) and time resolved pressure recordings. These techniques, however, suffer from a number of disadvantages mostly due to their intrusive nature, which for instance makes it quite difficult for them to resolve high level turbulence or work at extreme temperatures. The next step came with the possibility to use optical measurement techniques such as the laser Doppler anemometer (LDA) and particle image velocimetry (PIV). Both techniques require the introduction of so-called tracer particles to the flow. The displacement of these tracers is then measured by means of an optical system and a laser. LDA offers a high spatial resolution measurement (by scanning) but at only one position at a time, whereas the PIV offers full imagery of the flow at reduced resolution. The latter gives good results for resolving turbulence and with the correct tracer particles can operate in a wide range of temperatures.

However, if one is only interested in obtaining a qualitative visualization of the flow relatively quickly, choosing these correct tracer particles and tuning the test set-up could be overzealous. Using a laser Doppler vibrometer (LDV) it is possible to visualize flows without any intrusion whatsoever [3–5]. A LDV, which is traditionally used to measure vibrations is also sensitive to changes in refractive index of the medium, in casu density variations of the measurement volume along the line-of-sight. Therefore it is possible to measure e.g. flows or even acoustic phenomena. Moreover it is possible to retrieve this spectral information simultaneously, without hampering measurement time or needing a different test set-up. Now, it is well known that the signals acquired by interferometric techniques are line integrals over the laser beam optical path, so therefore images are often taken at different angles to derive local density distribution, which in turn implies

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needing tomographic reconstruction algorithms [6]. In this paper we are only interested in a 2-dimensional view of the flow and because of the specific nature of the test object no reconstructive tomography is necessary as will be shown in the following paragraphs.

In this paper the flow in a cylinder wake is visualized with an LDV, at different free stream velocities and for different sizes of cylinders. The frequency information, characterizing the von Karmann street in the wake of the cylinder, gained from the LDV measurements will be compared numerically to calculations done from the Strouhal number, computational fluid dynamics (CFD) calculations as well as a PIV measurement. As the technique does not give direct quantitative information on velocities, the measured density variations will be compared visually to the density calculated from CFD simulations.

2. Theoretical principle

The LDV is based on a modified Mach–Zender interferometer and measures a pseudo velocity depending on the variation of the optical path and the refraction index, n, of the medium within the measuring volume illustrated in Fig. 1.

The classical use of the LDV is to measure the velocity or displacement of moving objects on which the laser beam impacts. The physical principle governing the measurement system is the Doppler effect that occurs when the laser light is scattered by a moving target: if the laser light has a frequency υ, after being reflected from the object moving at velocity v, its frequency undergoes a shift $\Delta\upsilon$ given by

$$\Delta\upsilon = \frac{2v\cos\theta}{\lambda}, \tag{1}$$

where λ is the laser wavelength and $v\cos\theta$ is the target velocity component along the laser's line-of-sight. The system output is therefore the velocity v or the displacement s recovered from the frequency shift $\Delta\upsilon$; in our specific case it is the velocity. In this simplified theoretical discussion, it has to be pointed out that the measured displacement s not only depends on the optical path z of the laser beam, but also on the refraction index n of the medium through which the beam passes. Therefore, the velocity obtained from the interferometer is

$$\begin{aligned} v(x,y,t) &= \frac{\mathrm{d}s(x,y,t)}{\mathrm{d}t} = \frac{\mathrm{d}[n(x,y,t)z]}{\mathrm{d}t} \\ &= z\,\frac{\mathrm{d}n(x,y,t)}{\mathrm{d}t} + n(x,y,t)\,\frac{\mathrm{d}z}{\mathrm{d}t}. \end{aligned} \tag{2}$$

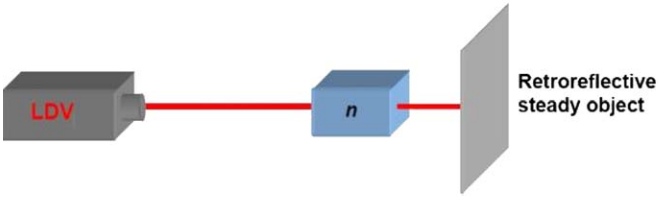

Fig. 1. Measuring principle.

When only the movement of an object is measured, the variation of the refraction index of the surrounding medium is zero and only the second term appears in Eq. (2), i.e. the velocity is given by the variation of the optical path. Vice versa, if one wants to measure turbulent fields the reflecting target is kept steady as is shown in Fig. 1. The only variable is the refraction index because the turbulence produces a temporal and spatial fluctuation of the air pressure, and consequently of the density, within the measuring volume. In reality the turbulence not only produces a flow velocity oscillation linked to turbulent effects occurring within the measuring volume but also a sound field fluctuation due to generated acoustic waves. This is the main advantage of this measuring technique because it allows broadband measurements up to very high frequencies which can normally not be detected with other apparatus.

However, a major drawback of the technique is that it only provides a visual representation of the flow and provides no quantitative information, besides the frequencies of the phenomena themselves. However, it is possible to extract information on the frequency content of the flow and compare this to the frequency content calculated from CFD simulations and PIV measurements.

In the next sections a comparison will be made between these two classical techniques and the technique described above using a LDV.

3. Experiment and simulation outline

3.1. Experimental set-up of LDV

The measurements were performed on two cylinders of different diameters ($\varnothing$ 0.014 and 0.062 m, respectively). They were suspended in a wind tunnel with a cross section of 30 × 30 cm. Three velocities were set to cover the entire range of the tunnel. The lowest stable free stream velocity setting was 11.2 m/s. The highest stable setting was 31 m/s. The third velocity was chosen arbitrarily in between the limits of the tunnel at 21.2 m/s. The velocities were measured with a pitot tube 0.5 m upstream of the cylinder.

As was stated in Section 1 the LDV measurement is a line integral over the optical beam length. Because the flow over a cylinder is 3-dimensional [7] the spanwise length L_z of the cylinder was chosen according to Eq. (3) in order to avoid having an even number of vortex periods in the spanwise direction. This would lead to measuring zero fluctuations with the LDV.

$$\frac{L_z}{\varnothing} \neq k, \tag{3}$$

where $k = 1, 2, 3, \ldots$.

The test set-up as it was used for the LDV measurements is shown in the schematic drawing in Fig. 2. The wind tunnel was equipped with a plexiglas section around the area of interest with wall thickness about 1 cm so as to allow the laser beam to pass through the wind tunnel to the