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A laser Doppler anemometry technique for Reynolds stresses measurement

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Abstract A technique is described for the measurement of all components of mean velocity and Reynolds stresses, in a complex turbulent flow where achieving coincidence data acquisition is difficult. The method is based on data recorded using four orientations of the laser probe. It is shown that the measurement errors are not the same for all the components of the Reynolds tensor, but they are sufficiently small to give a good accuracy. An application to a turbomachinery flow is given to illustrate the method.

1 Introduction

The measurement of Reynolds stresses is an important issue for turbulent flow diagnostics, and this can be achieved with a three-dimensional laser Doppler anemometer in coincidence filtering mode (a same seeding particle is validated through the three probe volumes at the same time). A first problem is that the intersection of the three probe volumes is six or seven times smaller than with a one-dimensional system. Moreover, for applications to internal flows such as turbomachinery, many drawbacks are caused by the presence of a cylindrical window between the flow and the optics (deviation of the beams, smoke deposits on the window) leading to very low data acquisition rates. While coincidence measurements have been successfully achieved in a low-speed axial turbine (Ristic et al. 1999), these drawbacks become important in high-speed compressors (Edmonds et al.1997). Nevertheless, the measurement of all components of mean velocity and Reynolds stresses in a complex turbulent flow has been described with a single hot-wire (Hoagland 1960) and with a crossed hot-wire (Cutler and Bradshaw 1991). These authors showed a technique that gives the components of the Reynolds tensor with measurements obtained in four roll positions of the hot-wire probe. To achieve this, they used only the two variances of velocity fluctuations along each hot-wire and the cross-correlation between them, measured for each roll position. Such a technique has been also applied to a single component laser system (Melling and Whitelaw 1976).

The aim of the present study is to develop this idea for applications to internal flows, where laser Doppler anemometry is a non-intrusive technique which has demonstrated great promise, including for multicomponent applications (Chesnakas and Dancey 1990; Stauter 1993; Strazisar 1986). The laser probe uses two laser heads; the first one is a two-dimensional measuring system tuned to the blue (488 nm) and green (514.5 nm) wavelengths. The second one is a one-dimensional measuring system tuned to the green–yellow (532 nm) wavelength. The velocity components relative to these colors are denoted by the subscripts b, g, y hereafter. A technique based on the recording of four different laser probe orientations is developed in order to process the six components of the Reynolds tensor, in addition to the mean velocity field.

2 Analysis

The heads are mounted on a robot arm, with the angle between their optical axes fixed to 2χ=30°. This gives sufficient resolution of the radial velocity in turbomachinery applications (Ristic et al. 1999). The laser probe frame of reference is defined relative to the compressor cylindrical frame of reference ($\boldsymbol{e}_z$, $\boldsymbol{e}_r$, $\boldsymbol{e}_\theta$) by the angles ϑ, ψ and φ, respectively the pitch, yaw and roll angle to the laser probe axis (Fig. 1). The color axes ($\boldsymbol{e}_b$, $\boldsymbol{e}_g$, $\boldsymbol{e}_y$) are the directions of measurement of the velocity for each laser component; $\boldsymbol{e}_g$, $\boldsymbol{e}_y$ are in the plane of the laser heads with an angle 2χ between them, $\boldsymbol{e}_b$ is orthogonal to this plane. These axes are written for any laser probe position as functions of (ϑ, ψ, φ). Four laser probe orientations are selected to obtain the alignment of one or two color components with the cylindrical coordinates. Four positions have been selected:

$$\begin{aligned}
&\text{position 1}: \vartheta = 0 && \psi = -\chi, && \varphi = 0\\
&\text{position 2}: \vartheta = 0 && \psi = \chi, && \varphi = 0\\
&\text{position 3}: \vartheta = -\chi, && \psi = -\chi, && \varphi = 0\\
&\text{position 4}: \vartheta = \chi, && \psi = -\chi, && \varphi = 0
\end{aligned}$$

As ($\boldsymbol{e}_b$, $\boldsymbol{e}_g$, $\boldsymbol{e}_y$) are not orthogonal axes, the successive orientations provide a maximum angular resolution in probe positioning and a minimal error in velocity estimates. The velocity is decomposed in mean velocity $\bar{U}$ and its fluctuation u, the averaging being either stationary or periodic, and the Reynolds tensor components are evaluated from the variances of color fluctuations.

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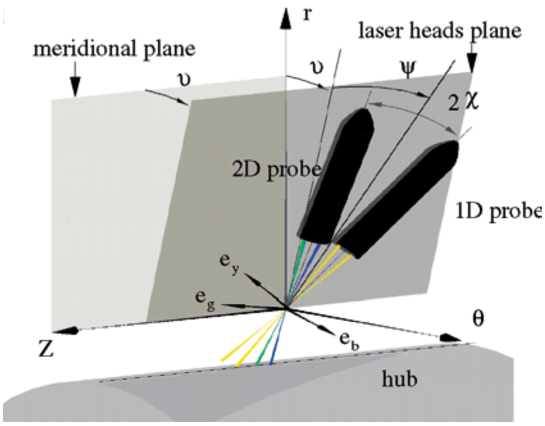

Fig. 1. Laser heads positioning relative to the compressor frame of reference

Any position provides the three components of mean velocity. However, to minimize the error they are calculated using orientations 1 and 2 only:

$$\bar{U}_z = \frac{\bar{U}_{g,1}+\bar{U}_{y,2}}{2}, \quad \bar{U}_\theta = \frac{\bar{U}_{b,1}+\bar{U}_{b,2}}{2}, \quad \bar{U}_r = \frac{\bar{U}_{g,2}+\bar{U}_{y,1}}{2\sin 2\chi}$$

The Reynolds stresses are obtained by:

$$\overline{u_z^2} = \frac{\overline{u_{g,1}^2}+\overline{u_{y,1}^2}}{2}, \quad \overline{u_\theta^2} = \frac{\overline{u_{b,1}^2}+\overline{u_{b,2}^2}}{2}$$

$$\overline{u_r^2} = \frac{\overline{u_{y,1}^2} + \overline{u_{g,2}^2} - \cos^2 2\chi\left(\overline{u_{g,1}^2} + \overline{u_{y,2}^2}\right)}{2\sin^2 2\chi}$$

$$\overline{u_z u_r} = \frac{\overline{u_{g,2}^2}-\overline{u_{y,1}^2}}{4\sin 2\chi\cos 2\chi}, \quad \overline{u_r u_\theta} = \frac{\overline{u_{b,4}^2}-\overline{u_{b,3}^2}}{4\sin\chi\cos\chi}$$

$$\overline{u_\theta u_z} = \frac{\overline{u_{y,4}^2} - \overline{u_{y,3}^2} + 4\cos^2\chi\sin^2\chi\left(\overline{u_{b,4}^2} - \overline{u_{b,3}^2}\right)}{8\cos\chi\sin^2\chi\left(\cos^2\chi - \sin^2\chi\right)}$$

Let us assume a constant absolute measurement error for the mean velocity of the color components η and for the variance of the color velocity fluctuations ϵ^2. It is then possible to calculate the absolute measurement error resulting in the procedure with four successive positions. The corresponding errors for the mean velocity and Reynolds stresses in cylindrical coordinates are given in Table 1.

Table 1. Measurement errors for mean velocity and Reynolds tensor

Quantity	Absolute error
$\overline{U_z}$	η
$\overline{U_\theta}$	η
$\overline{U_r}$	2η
$\overline{u_z^2}$	ε^2
$\overline{u_\theta^2}$	ε^2
$\overline{u_r^2}$	$7\varepsilon^2$
$\overline{u_z u_r}$	$1.15\varepsilon^2$
$\overline{u_z u_\theta}$	$2\varepsilon^2$
$\overline{u_\theta u_z}$	$5.58\varepsilon^2$

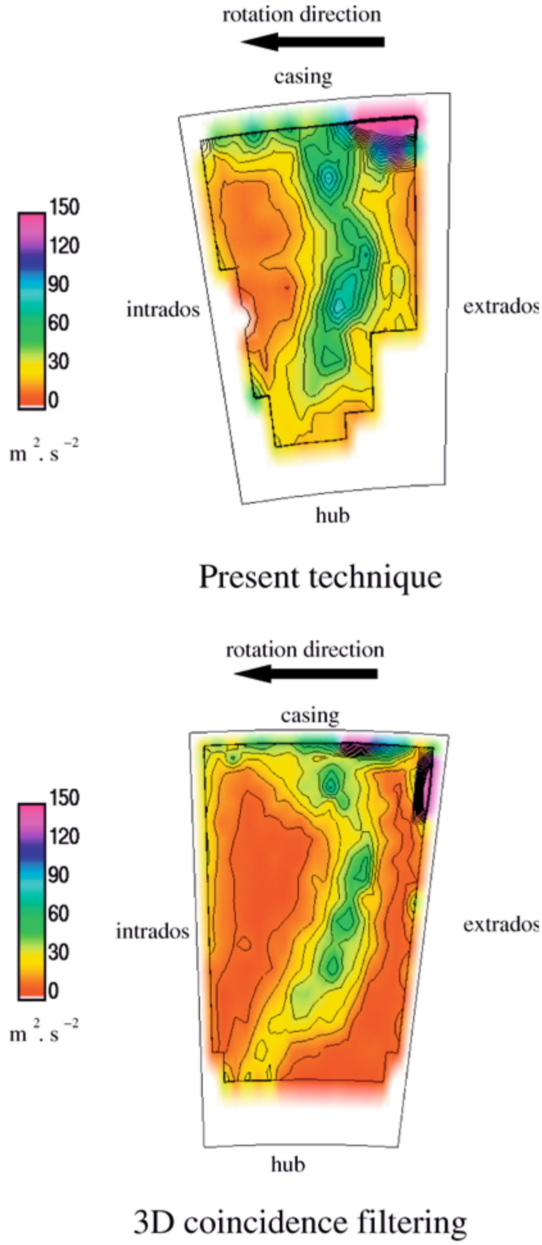

Fig. 2. Axial stress component measured with the present technique (*above*) and 3D coincidence filtering (*below*) for an axial distance situated at 66% of the chord inside the stator channel

3
Experiment

Velocities are obtained using a Dantec Burst Spectrum Analyzer processor based on the Fourier transform of the signal for determination of Doppler frequency.

The test rig is a single-stage axial compressor, providing a total pressure ratio of 1.15 for a flow rate of 10.5 kg/s and a nominal speed of rotation fixed at 6330 rpm. An extended description of the facility is available in (Faure et al. 2001).

4
Results

A comparison between the axial stress component measured with the present technique and 3D coincidence filtering mode is presented in Fig. 2. Measurements have been performed inside the stator row of the compressor for a mass flow rate of 10.5 kg/s, in an axial section located at two-thirds of the chord downstream of the stator blade leading edges. The grid of measurement is made up of 16×16 points. These maps are phase-averaged representations of the flow for a given time (each rotor blade passage relative to the stator channel being divided into 24 time intervals). Note for the instant and location chosen, the blade rotor wake is clearly visible in the middle of the stator channel. First, it is clear that the 3D coincidence filtering mode permits exploring a wider region of the channel than the present technique especially near the hub, due to the larger extent of the laser heads positions. Quite similar levels of the axial velocity fluctuations are found with the two methods. Particularly very high levels can be observed in the rotor blade wake and especially in the tip vortex and secondary flow near the casing. However, with the present technique the values observed are slightly higher than with the 3D coincidence filtering mode. It can be thought of as though the combination of two variances introduces a bit of artificial turbulence in the result. Nevertheless, the structures of the flow are practically identical with the two methods.

5 Conclusions

A technique for the measurement of Reynolds stresses in complex turbulent flows has been implemented. The method does not require the acquisition of coincident Doppler bursts for the three light components and is particularly useful for hard internal flow applications. It gives mean velocity and Reynolds stresses with a reasonable accuracy. The structures usually observed in compressor flows are well described.

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