Computer-aided calibration and measurements with a quadruple hotwire probe

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Abstract. A method for calibration and measurement with a four-wire probe is described. For each of the wires a three dimensional calibration field is determined, thus no assumption like King’s law or the cosine law need to be made. The velocity vector can then be detected in a fairly large angular range (± 40°) with a numerical search algorithm. First measurements in a free jet and a confined, strongly swirling flow are presented.

1 Introduction

Numerical models of turbulent swirling flows often show large discrepancies between the predicted velocity fields and the measurements. To validate and to improve these turbulence models (e.g. the k – ε turbulence model) the knowledge of the complete Reynolds-stress tensor field together with the mean velocity fields would be of great interest. Measuring these quantities with an LDA system would be possible if either three colors were used to determine all three velocity components simultaneously or by using two colors in two measurement positions as done by Hillemanns et al. (1986) (that means, for instance, radial and axial optical access to the swirl flow must be provided). A cheaper method limited to cold flows is to obtain the instantaneous velocities with a triple hot-wire probe, as used by Acrivellis (1979) and also by Butler and Wagner (1983). Unfortunately the three wire signals do not always define only one velocity vector (i.e. there are multiple solutions of the nonlinear system consisting of the three wire signal equations with the three unknown velocity components). To overcome that ambiguity, a four wire probe (Quadruple probe) was constructed which leads to an overdetermined system of four wire equations with three unknown velocity components, thus securing a unique solution.

2 Probe construction and calibration

The probe is composed of four slanted (45°) subminiature probes (micro-welded 2.5 μm platinum plated tungsten wires with approx. 0.7 mm length) which form a measuring volume of approximately 2 mm in diameter and 0.5 mm in height (Fig. 1). It is supported by a steel tube (7 mm in diameter) containing the wiring. The sensor angle of 45° was chosen assuming that the best angular resolution will be obtained with pairs of perpendicular wires. The four-channel, constant temperature anemometer is connected to a signal conditioner which transforms the bridge output voltage into a suitable range for the four-channel simultaneous-sampling A/D converter (12 bit) which itself is connected to a microcomputer (Fig. 2). The A/D converter allows a data rate of 8 kHz for each of the four channels. For calibration the probe is placed downstream of a nozzle. The plenum pressure upstream of the nozzle is measured with a pressure transducer connected to a fifth channel of the microcomputer’s A/D converter; thus the exit velocity of the nozzle can be calculated easily by Bernoulli’s equation. The usual wire equation is:

\[ F(S_p) = U_{n}^2 + h^2 + k^2 + U_r^2 \]

with

- \( S_p \) voltage,
- \( U_{n,b,r} \) normal, binormal and tangential velocity components.

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Here $F$ is, e.g., given by King's law; $h$ and $k$ are weighting factors for the binormal or tangential velocities as described in detail by Bradshaw (1971). The right hand side of Eq. (1) simulates the directional sensitivity of the wire and is often called the cosine law. The factors $h$ and $k$ and the direction of the wire with respect to the probe axis have to be determined experimentally. Slanted subminiatur probes do not follow this empirical cosine law with reasonable accuracy (Kutting and Sammler 1984) and the wire direction with respect to the probe axis is very difficult to determine accurately. Therefore a different signal equation was formulated for each wire:

$$f_i(S_p) = c^2 \cdot g_i(\Psi, \Theta)$$  \hspace{1cm} (2)

where $f_i$ is the linearization function, $S_p$ is the nozzle exit flow velocity, $\Psi$ is the angle of the velocity vector with respect to the probe axis (pitch), and $\Theta$ is the angle of the velocity vector with respect to the probe axis (yaw).

$c, \Psi$ and $\Theta$ are the magnitude and the directional angles, respectively, describing the velocity vector in a spherical coordinate system. The functions $f_i$ and $g_i(\Psi, \Theta)$ are determined experimentally in the following manner. Without any restriction $g_i(\Psi, \Theta)$ can be set to unity for $\Psi = \Theta = 0$, which means that the nozzle exit velocity is parallel to the probe axis. In this position, 1024 samples of the four wire voltages and the plenum pressure upstream of the nozzle are taken by the microcomputer while varying the velocity over the desired calibration range. With these samples the four linearization functions $f_i(S_p)$ are fitted using the least squares sum algorithm with polynomial of the 9th order, which gives a somewhat lower standard deviation to the data points (less than 0.2 m/s) compared with lower (e.g. 4th) order polynomials. Figure 3 shows the data points along with the polynomial. Due to the low standard deviation the datapoints almost coincide with the polynomial with exception of the very low velocities where small plenum pressure variations (or digitizing errors of the A/D converter) result in large velocity variations (this also causes the polynomial to become slightly negative). When the linearization functions are known the microcomputer samples the function values of $g_i(\Psi, \Theta)$ by varying automatically $\Psi (-60^\circ < \Psi < 60^\circ)$ and $\Theta (-40^\circ < \Theta < 40^\circ)$ amongst 117 discrete angular positions (13 $\Psi$ and 9 $\Theta$ angles) through stepping motors while the nozzle output velocity is kept constant. The functions