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MULTI-HOT-WIRE PROBES FOR 3-D MEASUREMENTS OF TURBULENT VELOCITY FIELD

Abstract

Contemporary multi-hot-wire probes, specified for three-dimensional instant measurement of turbulent velocity field, are reviewed. In addition, basic operational principles of the newest hot-wire configurations designed for vorticity measurement as well as for very accurate measurement of fluctuating fluid velocity components are described. Special attention is paid to the analysis of influence of the hot-wires configuration and sensing volume dimensions on the probe measurement accuracy and applicability range (uniqueness domain).

MULTISENZORSKE SONDE SA ZAGRIJANIM VLAKNIMA ZA MJERENJE TRODIMENZIONOG TURBULENTNOG STRUJNOG POLJA

Izvod

U radu je dat pregled savremenih multisenzorskih sondi sa zagrijanim vlaknima za trodimenziono mjerenje karakteristika turbulentnih strujnih

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polja. Dati su, takođe, i osnovni principi najnovijih konfiguracija sondi konstruisanih za mjerenje vrtložnosti i veoma precizno mjerenje komponenti fluktacija turbulentnog brzinskog polja. Posebna pažnja je posvećena analizi uticaja konfiguracije zagrijanih vlakana i dimenzija mjernog prostora na tačnost mjerenja i oblast primjene sondi.

1. INTRODUCTION

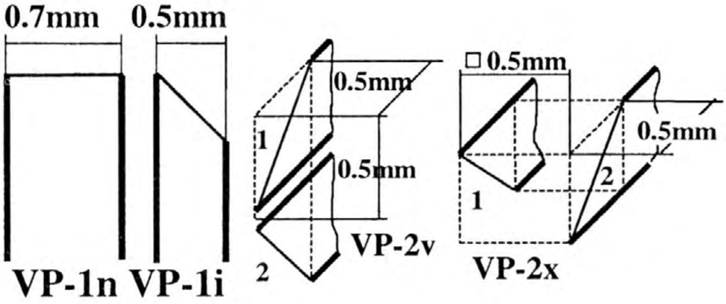
Besides the multiple hot-wire anemometer probes, specified for subsonic isothermal turbulent velocity field measurements, and ultramodern vorticity probes, capable of simultaneous velocity and vorticity measurements, the older version of single-wire probes and „*X*" and „*V*" configurations with two sensors still deserve attention because of their simplicity and applicability in a wide area of engineering problems. Triple-sensor probes are interesting as the first instruments capable of simultaneous measurements of all three velocity components as well as the logical step toward the four-sensor probes designed for the same purpose. However, a number of excellent textbooks and scientific papers, where corresponding references about these probes are discussed and summarised, currently are available. Among many others, the following should be mentioned: *Kovasznay 1954*, *Hinze 1959*, *Corrsin 1963*, *Bradshaw 1971*, *Sandborn 1972*, *Comte-Bellot 1976*, *Vagt 1979*, *Blackwelder 1981*, *Perry 1982*, *Freymuth 1983, 1992*, *Fingerson and Freymuth 1983*, *Lomas 1986*, *Muller 1987* and *Bruun 1995*.

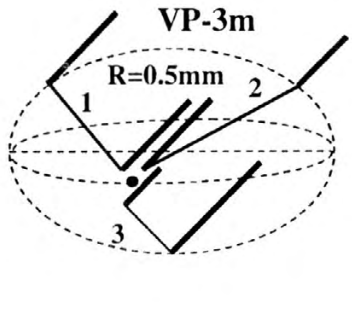
2. HOT-WIRE PROBES DESIGN

Nowadays, a variety of hot-wire probes with different number of sensors and their configurations exists. Especially after introducing digital computers in the experimental practice in the early 1970's, the range of hot-wire probes applicability is crucially enlarged. Digital computers allowed very complex probes to be employed for experimental purposes and in the industry use. Most of hot-wire probe configurations used in the experimental practice are sketched in fig. 1 and listed in the following text. They are also available at the University of Montenegro in Podgorica.

- Normal single wire probe ***VP-1n***, used for measurement of one component of fluid velocity vector normal to the wire axis of symmetry. This probe can be manufactured to the smallest dimensions in comparison to the other existing configurations. However, it demands neglecting of other two velocity components, what sometimes generates significant measurement errors.

- Slanted wire configuration ***VP-1s*** is specified for measurement of several statistical moments of turbulent velocity, placing it sequentially at various different orientations toward the main flow. In this case, results suffer from the similar problems, as is the case with previous one.
- „**V**" and „**X**" probes with two wires (***VP-2v***, ***VP-2x***) are used to measure two velocity components in the centre of their measuring volume. The lack of the third sensor demands neglecting the third component during output signals interpretation. If the fluid velocity vector is not in the plane of sensors, this approximation can produce significant measurement errors. This is one of the worst disadvantages of stationary single and X-wire probes, which reduces their applicability to flows with low turbulence levels.
- Contemporary triple-wire probes are usually designed with mutually orthogonal sensors, giving the front view of „Mercedes" symbol (***VP-3m*** geometry). However, simpler „**T**" configuration that corresponds to ***VP-3t*** probe is used sometimes. It provides lower uniqueness domain, but the procedures for signal interpretation are much simpler. Both „**T**" and „**M**" configuration enable simultaneous measurement of instant values of all three fluctuating velocity components.





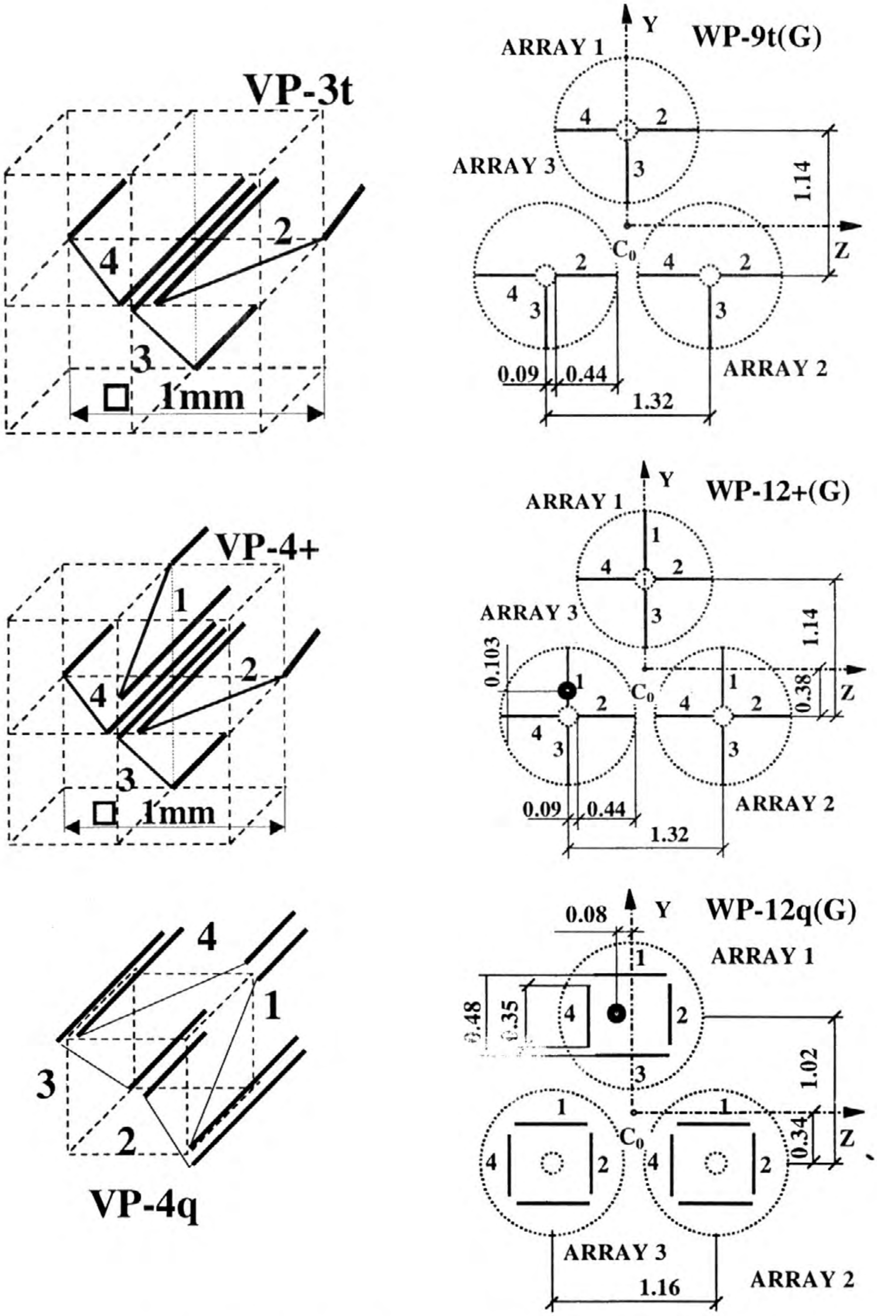


FIG. 1: Sketches of typical hot-wire probe configurations.

Four-wire probes are designed in two different sensor configurations: „plus" ***WP-4+*** and „quadruple" ***WP-4q***. These probes are capable of simultaneous instant measurements of all three velocity components, having much larger uniqueness range then triple-wire probes.

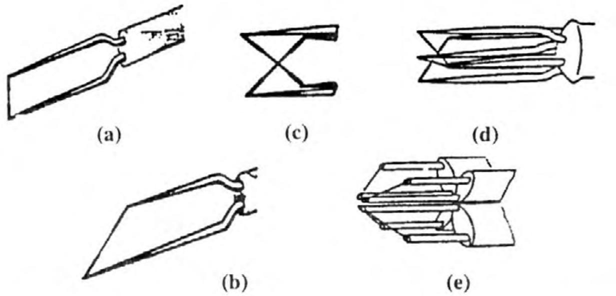


FIG. 2: Typical probes with strait-prongs: (a) normal-wire *DANTEC 55P11*, (b) slanted-wire *DANTEC 55P12*, (c) „X" probe *DANTEC 55P61*, (d) triple film probe *TSI-1299* and (e) four- wires probe of *Dobelling, Leuckel and Lenze 1990a, b.*

- Nine-wire probe ***WP-9t(G)*** enables simultaneous three-dimensional measurement of instant velocity components and their gradients in the plane normal to the probe axis. Measurement of all vorticity components is also possible.
- Twelve-sensor configurations ***WP-12+(G)*** and ***WP-12q(G)***, with three „plus" or „quadruple" arrays respectively, represent a further logical step in the vorticity probes development after ***WP-9t(G)***. However, these probes possess the arrays that allow measurements of instantaneous velocity vector which forms a wider range of angles with respect to the probe axis than it is possible using three-wire arrays, as is the case with ***WP-9t(G)***.

Besides the above listed probes, some researches also use their own technologies for hot-wire anemometer probes design and manufacturing. However, for standard applications, the most frequently used probes are those of world famous manufacturers DANTEC (Denmark) and TSI. (USA) Their popularity originates primarily from the standard (guaranteed) quality and provided technical support. These probes are presented, together with „plus" probe of *Dobelling, Leuckel and Lenze 1990a, b*, in fig. 2.

	Tungsten	**Platinum**	**80%Pt+20%Ir**
Temp. coef. of resistance α(1/K)	0. 0045	0. 0039	0. 0008
Resistivity (Ω m)	5.5×10^{-8}	10×10^{-8}	31×10^{-8}
Ultimate tensile strength (N/mm^2)	4120	241	981
Thermal conductivity (W/m K)	197	70	17. 6

TAB. 1: Some physical properties of commonly used wire materials. (Source: *Fingerson & Freymuth 1983)*.

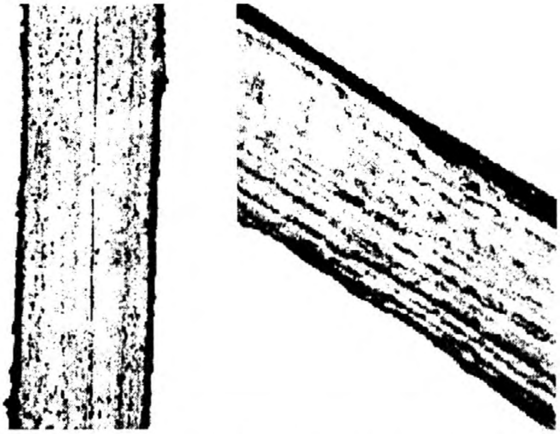


FIG. 3: Hot wires magnified under microscope: 80%Pt+20%Ir, d=2. 5 mm (left) and 100% tungsten, d=3. 8 mm (right). (Source: *Blackwelder 1981*).

The most commonly used materials for hot wire sensors are tungsten, platinum, platinum-rhodium (90%Pt + 10% Ro) and platinum-iridium (80%Pt+20%Ir). Their physical properties are rewritten in table 1. Magnified photographs of the surfaces of hot wires, containing 80% Pt+20%Ir (d=2. 5mm) and 100% tungsten (d=3. 8mm), are presented in fig. 3.

Tungsten wires have a high temperature coefficient of electric resistance and the highest tensile strength. However, according to *Blackwelder 1981*, this material can be used only at fairly low operating temperatures, under 350^{0}C. This restriction originates from poor oxidation resistance of tungsten at high temperatures. Platinum possesses a good anti-oxidation resistance and can be produced in very small diameters, up to 0. 5mm. Unfortunately it is weak, especially at high temperatures. Alloy containing 80% of platinum and 20% of iridium represents a compromising hot-wire material. It has good anti-oxidation properties, acceptable tensile strength, but low temperature coefficient of electric resistance. In accordance with its properties, this alloy finds applications in the situations when wire temperature is too high for tungsten and platinum. However, tungsten wires are still used in most airflow studies.

The choice of hot wire diameter is a question of compromise. Main advantages of its small value are improved signal-to-noise ratio at high frequencies, increased frequency response and spatial resolution, reduced flow interference and sensor end-conduction losses. However, large value of wire diameter increases its strength, but reduces sensitivity due to the particles presence in fluid etc. Experimental practice shows that an optimum value of wire diameter should be in the range between 2mm and 5mm.

The situation is analogous in the case of hot-wire length choosing. While short sensors maximise the spatial resolution and minimise the aerodynamic loading, long wires minimise end-conduction losses and provide more uniform temperature distribution. The question of the best compromise for the wire length-to-diameter ratio is differently resolved by various turbulence researches. In accordance to *Ligrani and Bradshaw 1987* and *Turan and Azad 1989*, it should be at least around 200. Some other designers of hot-wire probes, like *Vukoslavčević, Wallace and Balint 1991*, applied hot-wire probes with the aspect ratio of 280. Worldwide known manufacturer, DANTEC, mainly uses the aspect ratio L/d=250 for their standard probes (a few of them are sketched in fig. 2).

Hot-wire is either attached directly to the tips of the prongs or through its plated ends. The central unplated part of the sensor represents the active sensing length. Plating of hot-wire ends efficiently define the sensing length of the wire and reduces the heat flux dissipated by the prongs. It also results in a more uniform temperature distribution along the unplated part of a wire. The additional advantage of probes with plated sensor ends, over unplated, is the reduction of flow disturbances at the measurement point. This property is achieved thanks to the wider distance between the prongs and active (sensing) part of a wire. *Fiedler 1978* verified large discrepancies between the static and dynamic calibration of unplated hot-wire probes. However, according to *Bruun 1976* and *Fiedler 1978*, both types of calibrations gave nearly the same results for the probe with plated sensors.

Elements of hot-wire probe, primarily stem and prongs, aerodynamically disturb the flow. These disturbances change the velocity field over the sensor in comparison to the undisturbed flow. Systematic studies of these phenomena are reported by *Comte-Bellot, Strohl and Alcaraz 1971, Strohl and Comte-Bellot 1973, Adrian, Johnson, Jones, Merati and Tung 1984, Merati and Adrian 1984, Dobbeling, Lenze and Leuckel 1990a, Holzapfel, Lentze and Leuckel 1994*, etc. They provided general information for hot-wire probes design and formulation of suitable calibration procedures and algorithms for their output signals interpretation.

One of the most complicated problems in hot-wire anemometry is connected with thermal interference between various probe elements (sensors primarily). It is caused by the thermal wake behind a heated wire, which intercepts the other sensor of the same multiple-probe, or the wire in a closely positioned neighbour-probe. Thermal interference has been in focus of interest of many researches. *Ko and Davis 1971, Jerome, Guitton and Patel 1971* and *Strohl and Comte-Bellot 1973* have studied this problem in the case of single and X-wire probes. In addition, more complex multiple-wire configurations with four, nine and twelve sensors are tested (among others) by, *Vukoslavčević, Wallace and Ballint 1991*.

3. HEAT TRANSFER FROM A HEATED WIRE

The electrical heat, created in the hot-wire through the Joule's effect, is transferred to its environment by convection, conduction and radiation. In accordance to *Bruun 1995*, connection between the output voltage of hot-wire probe **E** and voltage drop along its sensor $\mathbf{E_W}$ can be described by the following expression:

$$E = \frac{R_P + R_L + R_W}{R_W} \cdot E_W, \tag{1}$$

where $\mathbf{R_P}$, $\mathbf{R_L}$, and $\mathbf{R_W}$ denote probe, cable and wire operating resistance, respectively. Following (1), for a constant-temperature anemometer, the electrical heat input $\mathbf{Q_E}$ is given by:

$$Q_E = \frac{E^2 \cdot R_W}{(R_W + R_L + R_P)^2} = Q_C + Q_\lambda + Q_R \tag{2}$$

where $\mathbf{Q_C}$ is the convective heat transfer from the wire to the fluid, $\mathbf{Q_\lambda}$ the conductive heat loss toward sensor prongs and $\mathbf{Q_R}$ represent the radiation flux.

Convective heat transfer from a heated wire placed into the flow depends on both the physical properties of ambient fluid (density ρ, viscosity μ, thermal conductivity λ, specific heat $\mathbf{c_P}$ etc.) and the flow parameters (velocity vector $\mathbf{U_0}$, fluid temperature $\mathbf{T_A}$, pressure **p**, etc). Corresponding relations are often expressed in non-dimensional terms, such as Nusselt (**Nu**), Reynolds (**Re**), Prandtl (**Pr**) Grashof (**Gr**) and Mach (**Ma**) number:

$$Nu = \frac{K \cdot d}{\lambda}, \tag{3}$$

$$Gr = \frac{g \cdot \rho^2 \cdot d^3 \cdot \beta \cdot (T_W - T_A)}{\mu^2}, \tag{6}$$

$$Pr = \frac{c_P \cdot \mu}{\lambda}, \tag{4}$$

$$Re = \frac{\rho \cdot U_0 \cdot d}{\mu}. \tag{7}$$

$$Ma = \frac{U_0}{c}, \tag{5}$$

The following designations are used:

K – convective heat transfer coefficient;
μ – dynamics viscosity of the fluid;
ρ – density of the fluid;
g – gravitational acceleration;
β – volume coefficient of expansion;
T_W – operational temp. of the wire;
T_A – temperature of the ambient fluid;
c – the speed of sound;
U_0 – flow velocity;
d – diameter of a heated cylinder;
c_P – fluid specific heat at a constant pressure.

In comparison with wires, prongs are much more massive. Their temperature is therefore fairly close to the time-mean value of ambient air temperature. Since the wire is operated at significantly higher temperature, conductive heat transfer will take place toward the prongs. The final consequence is a temperature distribution within the sensing element (its ends will be at lower temperature than the central part).

Under normal operating conditions, the radiation losses are about 0. 01% of heat input to the wire (*Comte-Bellot 1976*) and can be neglected, as it is done here. However, radiation heat losses can be important in the low-density fluids and near solid surfaces.

If the conductive heat loss $\mathbf{Q_\lambda}$ is neglected, the anemometer output voltage can be directly related to the fluid velocity. Although a wide variety of corresponding expressions for heat-transfer exist, almost all of them are based on Nusselt number

$$Nu = \frac{K \cdot d}{\lambda} = \frac{Q_C}{\pi \cdot L \cdot \lambda_F \cdot (T_W - T_A)}, \tag{8}$$

where **L** is the active wire length and $\boldsymbol{\lambda_F}$ is the fluid conductivity at „film" temperature

$$T_F = (1/2) \cdot (T_W + T_A) \cdot \tag{9}$$

Corrsin 1963 suggested a general expression for the Nusselt number:

$$Nu = Nu(Re, Pr, Ma, Gr, Kn, L/d, a_T, \kappa, \phi), \tag{10}$$

where ϕ is the angle between the wire axis and fluid velocity vector and $\mathbf{k=c_p/c_v}$ is the ratio of specific heats.

General expression (10) can be fortunately simplified in the most of practical applications. In the situations involving **Ma**<0. 3, compressibility effects can be neglected and Mach number **Ma** and specific heat $\mathbf{c_P}$ can be considered as constants. Relevant parameter for low-density flows is Knudsen number **Kn=l/d**, where **l** is molecular free path. This number is related to the Mach and Reynolds numbers by:

$$Kn = \left(\frac{\kappa \cdot \pi}{2}\right)^{1/2} \frac{Ma}{Re}. \tag{11}$$

The rarefied-gas effects are negligible when the sensor diameter **d** is large enough in comparison to the mean free path of the fluid molecule **l** (**Kn**<0. 01). In addition, natural convection from the wire becomes important only at very slow fluid motion. In accordance to *Lekakis 1996*, for a typical wire, this occurs at fluid velocity under 5 cm/s. Its effects can be expressed as a function of Grashof number **Gr**. *Collis and Williams 1959* performed the air-experiments with large aspect ratio **L/d** sensors and concluded that buoyancy effect can be neglected when $\mathbf{Re>Gr^{1/3}}$. Having on mind that this manuscript is limited to non-compressible isothermal airflow, high-velocity and low-density flows are not discussed here. Corresponding additional information about these flows can be found in the available monographs, such is *Bruun 1995* for example.

Assuming **Pr**=0. 72 for the air and constant values of ϕ, **k** and $\mathbf{a_T}$, equation (10) reduces to:

$$Nu = Nu(Re). \tag{12}$$

Early heat-transfer relationships were developed in this form. Following the work of *King 1914*, the convection heat transfer for the infinite wire placed in the potential flow is often described by formula

$$Nu = A + B \cdot Re^{0.5}, \tag{13}$$

where **A** and **B** are empirical constants for each fluid and probe. It has been established in the literature that an exponent of 0. 45 provides a better correlation than a value of 0. 5 in the Reynolds number range encountered in the hot-wire anemometry (*Lekakis 1996*). *Collis and Williams 1959* suggested a formula for the air measurements

$$Nu = \left(A + B \cdot \mathrm{Re}^{N}\right)\cdot\left(1 + a_T/2\right)^{0.17}, \tag{14}$$

where $a_T = (T_W - T_A)/T_A$ and: $N=0.45, A=0.24, B=0.56$ for $0.02<Re<0.44$
$N=0.51, A=0.00, B=0.48$ for $0.44<Re<140$.

Expressions (13-14) are valid for airflows only. However, *Kramers 1946* analysed the results of heat-transfer experiments for heated elements placed in air, water and oil. Using the formula

$$Nu = 0.42 \cdot Pr^{0.26} + 0.57 \cdot Pr^{0.53} \cdot Re^{0.50}, \tag{15}$$

he obtained satisfactory results in the ranges 0. 01<**Re**<10^4, 0. 71<**Pr**<525 and 2<**Nu**<20.

Fluid properties μ, ρ and λ are temperature dependent. They are evaluated at the absolute „film" temperature $\mathbf{T_F}$. The non-dimensional **Nu** and **Re** numbers also depend on the reference temperature used. Many scientists analysed the influence of fluid temperature on the measurement results of turbulent velocity field. Their results are available in the classic literature, like *Bruun 1995*.

Heat transfer mechanism of a heated wire placed in fluid flow is extremely complex. It has been in the focus of researcher's interest from the origin of hot-wire anemometry, but is not completely resolved yet. The accurate basic equation of hot-wire anemometry still does not exists. Fortunately, a lack of agreement in this case can be resolved by involving the probe calibration before measurements into experimental practice of hot-wire anemometry.

4. DIRECTIONAL SENSITIVITY OF A WIRE OF FINITE LENGTH

Expressions presented in the previous section assume hot-wires of sufficient aspect ratio, when conductive heat transfer from the sensor ends to the prongs can be neglected. However, following *Wyngaard 1969*, spatial resolution criteria impose sharp restrictions on dimensions of hot-wire probes and their sensors. These limitations very often demand application of wires with aspect ratio, which is not large enough to allow neglecting of the conductive heat transfer from the sensor toward its supports. Following *Nitsche and Haberland 1984* and *Pitts and McCaffrey 1986*, for example, conductive losses have to be accounted in these situations.

The most common approach to describe the directional dependence of finite hot-wire heat transfer involves the effective cooling velocity $\mathbf{U_E}$. For an infinitely long sensor, placed in the potential flow, it is related to fluid velocity $\mathbf{U_0}$ by well known „cosine law" (see *Corrsin 1963* for example):

$$U_E = U_{N0} = U_0 \cdot cos\phi \cdot (16)$$

Directional sensitivity of real wires doesn't follow tightly „cosine law" (16), because of end-conduction losses toward the prongs and their finite length. *Hinze 1959* included these effects in response equation:

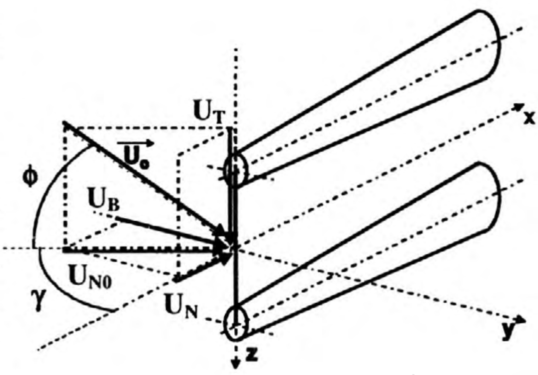


FIG. 4: Fluid velocity components in the local Decartes co-ordinate system of hot-wire.

$$U_E = |U_0| \cdot \sqrt{cos^2\phi + k \cdot sin^2\phi}, \tag{17}$$

where **k** denotes jaw coefficient which has to be evaluated by the probe calibration. *Fujita and Kovasznay 1968* have suggested an alternative expression:

$$U_E = |U_0| \cdot [cos\phi + e \cdot (cos\phi - cos\,2\phi)] \cdot \tag{18}$$

Friehe and Schwatz 1968 joined them with the formula:

$$U_E = |U_0| \cdot \left[1 - b \cdot \left(1 - \sqrt{cos\phi}\right)\right]^2, \tag{19}$$

where **e** and **b** are constants determined by calibration. Formulas (18) and (19) are more accurate for certain applications. However, the experimental comparative tests, performed by *Bruun, Nabhani, Al-Kayiem, Fardad, Khan and Hogarth 1990* and *Adrian, Johnson, Jones, Merati and Tung 1984*, indicate that Hinze's formulation gives the best fit in the pure jaw tests.

Besides effects described by expressions (17-19), the additional aerodynamic blockage effects of the fluid passing through the opening bounded by the sensor, prongs and probe stem can occur (see *Comte-Bellot, Strohl and Alcaraz 1971* and *Adrian, Johnson, Jones, Merati and Tung 1984*). They are especially important when the probe angle toward the instant flow direction is high. In order to account them, *Jorgensen 1971* suggested the following equation for the effective cooling velocity:

$$U_E^2 = U_N^2 + k_T{}^2 \cdot U_T^2 + k_B{}^2 \cdot U_B^2, \tag{20}$$

where $\mathbf{U_B}$ is the binormal velocity component in the wire local Decartes co-ordinate system sketched in fig. 4. The pitch calibration coefficient $\mathbf{k_B}$ has to be determined experimentally. Its value reaches minimum for end-plated sensors (*Jorgensen 1971*).

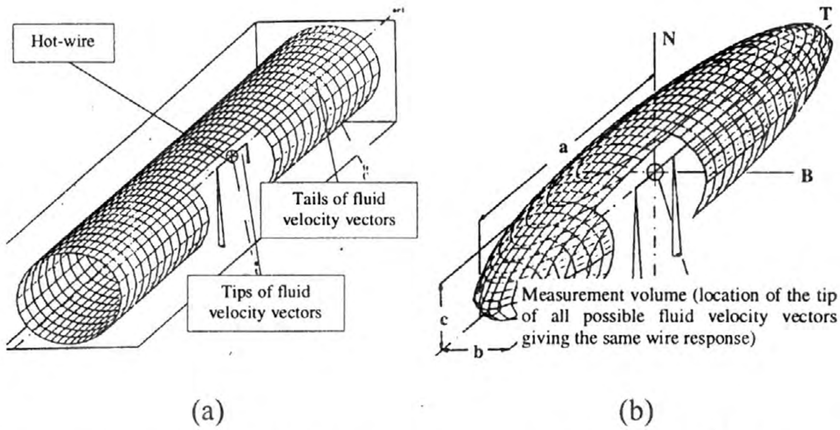


FIG. 5: Graphical illustration of fluid velocities giving the same signal of hot-wire:
(a) indefinitely long (ideal) sensor, according to *Willmarth 85* and
(b) real sensor of finite length, according to *Dobbeling, Lenze & Leuckel 1990a*, who followed expression of *Jorgensen 1971*.

A graphical representation of the single-wire directional response equation (16) is given by *Willmarth 1985* – see fig. 5(a). He showed that indefinite number of possible fluid velocity vectors with various intensities and directions, giving the same wire response, exist. Their tips lay on the centre of the sensor and the tails are on the cylinder of indefinite length. Even more, he showed that an indefi-

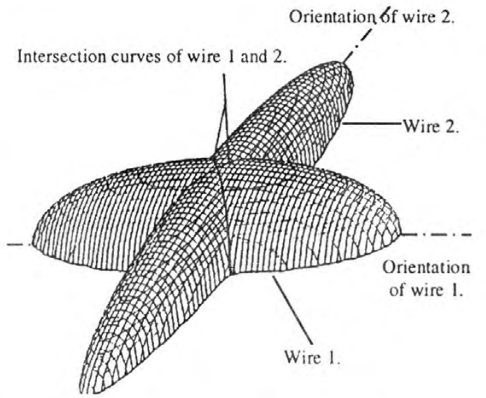


FIG. 6: Orthogonal X-probe directional response, following *Dobbeling, Lenze and Leuckel 1990a*.

nite number of possible fluid velocity vectors with the *same* intensity but various directions, giving the identical wire response, exists in the plane normal to the wire axis.

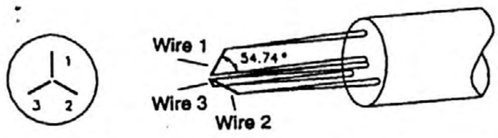


FIG. 7: Orthogonal geometry for triple hot-wires probes. Source: *Rosemann 1989*.

As an extension of *Willamarth's 1985* ideas, more realistic probe behaviour with full Jorgensen's equation (20) was analysed by *Dobbeling, Leuckel and Lenze 1990a*. It is graphically illustrated in fig. 5(b) by an offline contraction of a rotational ellipsoid with characteristic dimensions giving $\mathbf{c/b=k_T}$ and $\mathbf{c/a=k_B}$.

The same authors also analysed multiple solutions of response equations for X-probe with orthogonal sensors and prongs lying in the parallel planes (assuming that one should be very close to the other). They obtained graphical illustrations of Jorgesen's non-linear expression (20), presented in fig. 6. In this case, two intersection curves exist that satisfy both wire response equations, giving therefore the infinite number of solutions for the instantaneous velocity vector.

Triple-wire probes are most commonly designed with orthogonal sensors (fig. 7). In that case, it is suitable to assume that the wires are oriented in such a way that they form a local Decartes co-ordinate system. From the condition of probe summetry, it follows that the axis of that coordinate system form an angle of 54.74^0 with probe axis. For this geometry, known as „Mercedes" configuration, *Dobbeling, Lenze and Leuckel 1990a* showed that symmetrical behaviour of hot-wire heat-transfer enables mirror-imaging of flu-

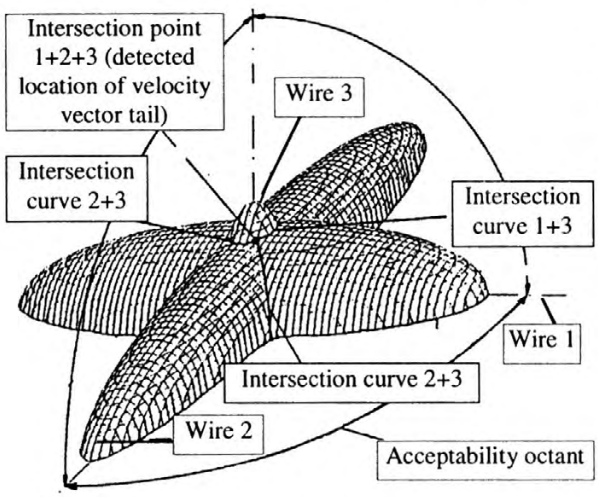


FIG. 8: Directional response of an orthogonal triple probe, following the empirical law of *Jorgensen 1971*. Source: *Dobbeling, Lenze and Leuckel 1990a*.

id velocity vectors for the wire response equation (20) with the planes defined by two of the local co-ordinates.

They concluded that in general there are 8 velocity vectors of the same magnitude, which gave the same wire signal (see fig. 8). Thus, the uniqueness range is restricted to only one of eight octants. In order to avoid uncertainty about uniqueness, the measured velocity vectors must be in the cone that can be placed in one of eight octants having the half angle of 35, 26^0. This means that the allowed inclination of velocity vector toward the probe axes is 35. 26^0. If some of the measured values are on the edge of this cone, the probe probably does not give unique solutions. Even this limited half-angle represents the theoretical value, which can not be achieved with the real probes. In the special cases, when one or two of velocity components are zero, there will be only four or two mirror imaged vectors, respectively.

5. HOT-WIRE PROBES FOR 3-D TURBULENT VELOCITY MEASUREMENTS

Turbulent fluid motion is three-dimensional by its nature. The special unique mechanism of turbulence maintaining, known as vortex stretching (*Tennekes and Lumley 1978*), can not exist in two-dimensional flows. In addition, contemporary technical problems in turbulent shear flows very often involve situations in which three-dimensionality is highly expressed. Typical examples are flows over large roughness elements, near wakes behind axisymmetric bodies, swirling jets, etc.

In these cases, high turbulence levels make employment of single or two-wire probes non-adequate. This is caused by the measuring principle of single and two-sensor probes. They demand neglecting of the one or two fluid velocity components respectively, which produce measuring errors on the measured components. The errors increase with increasing the magnitude of neglected velocity component. Operational applicability of X-wire probes has been extensively studied in the various flows by many researches: *Chang, Adrian and Jones 1983, Nithianandan, Jones and Adrian 1987, Muller 1992, Ong and Wallace 1996*, etc. Using computer-generated Gaussian signals of specified statistical moments, *Kawall, Shokr and Keffer 1983* found that this error is negligible for turbulence intensities smaller than 15%. Furthermore, they reported that the error due to the cross-velocity in X-wires becomes important for higher-order velocity moments. They concluded that all three components of fluid velocity vectors should be measured even in the flows with medium turbulence levels over 15%.

The problem described above can be sometimes resolved by applying probes with three hot-wires, which enable simultaneous instant measurement of all three components of fluid velocity. *Fabris 1978, Moffat, Yavuzkurt and Crawford 1978, Accrivellis 1979, Huffmann 1980, Accrivellis 1980, Lakshminarayana 1982, Andreopulos 1983, Buttler and Wagner 1983, Chang, Adrian and Jones 1983, Mathioudakis and Breugelmans 1984, Muller 1987, Buddhavarapu and Meinen 1988, Lekakis, Adrian and Jones 1989*, etc. reported applications of triple-wire methods. However, the analysis presented in the previous section, shows the serious restriction in applicability of triple-wire configurations. They are limited to a certain angular range where their output signals enable unique determination of fluid velocity vector. It is usually represented by a conical surface, which axis is coincident to the probe axis and is denoted as „uniqueness cone" (for illustration see fig. 9).

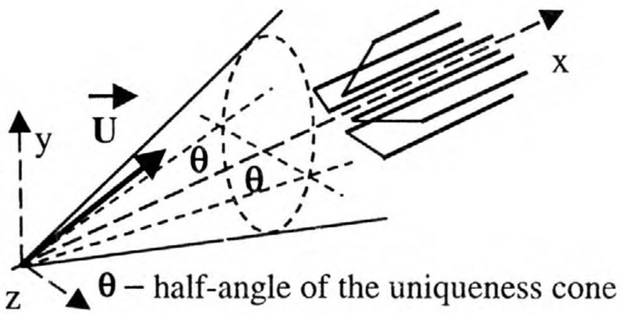


FIG. 9: A sketch defining the uniqueness cone.

In highly turbulent flows, the possibility of confusion always exists between different velocity vectors that correspond to the same set of triple probe output voltages. *Tutu and Chevray 1975* referred this as „rectification error" in their study of accuracy of turbulent velocity field measurement by X-probe. Uniqueness domain of multi-wire response equations has been also investigated by *Willmarth 1985, Samet and Einav 1987, Lekakis 1988, Lekakis, Adrian and Jones 1989, Vukoslavčević and Wallace 1983, Vukoslavčević, Wallace and Balint 1991, Rosemann 1989, Dobbeling, Lenze and Leuckel 1990a, b, Vukoslavčević and Petrović 1994, Petrović and Vukoslavčević 1995*, etc.

Difficulties originated from restricted applicability domain of stationary triple-wire probes can be generally resolved in a few main directions. The first is to employ the other techniques, such as laser-Doppler anemometer (LDA), which enables velocity measurement in the highly turbulent and even in some recirculation flows. However, stationary hot-wire techniques (HWA) are less expensive than LDA and are more suitable in velocity measurements in gases where high frequency response and low noise are required (*Holzapfel, Lentze and Leuckel 1994*). This is particularly the case when flow data are needed to test closure hypothesis in turbulence models, which demand measurement of higher moments of velocity fluctuations and power spectra. The latter demands the capability of coincident and time-equidistant high-frequency data sampling from measurement technique (not available with LDA), in order to perform such data analysis as the fast Fourier transform (*Holzapfel, Lentze, Leuckel 1994*).

Besides LDA, a flying hot-wire could be also used in highly turbulent flows. However, it suffers from some operational restrictions similar to LDA, such as low frequency of data sampling, for example. In addition, flying wire is operationally very complicated, because of the necessity for employing special traversing mechanism. Their measuring principle, based on continuous oscillatory movement, usually makes these probes less reliable in comparison to stationary probes.

From the reasons mentioned above, stationary multiple hot-wire techniques have been extensively used for many years in a great number of applications. Currently, researches invest great efforts for further improvement of their design. Triple-wire probes are commonly constructed with orthogonal sensors (fig. 7). According to *Dobbeling, Lenze and Leuckel 1990a*, this configuration maximises the differences in the wire voltages because each wire is sensitive only in its normal and binormal direction and relatively insensitive in its tangential direction. The voltage differences between the wires yield the information, which determines the direction of the velocity vector. Therefore, orthogonal probes will have maximum angular sensitivity. However, *Lekakis, Adrian and Jones 1989*, as well as *Rosemann, Stager and Kreplin 1989*, claimed different reason for the popularity of orthogonal triple-wire configuration: this design is a compromise between the size of uniqueness domain and probe angular sensitivity.

At present two general approaches for enlarging the uniqueness range of the stationary probes for 3-D measurement of turbulent velocity field exist. The simplest is to apply special non-orthogonal configurations, as it was done by *Acrivellis 1980* and *Kawall, Shokr and Keffer 1983*. However, *Roseman 1989* and *Lekakis, Adrian and Jones 1989* showed that such non-orthogonal set-up also reduces the total angular sensitivity of the probe. The final consequence is expressed in larger angular errors in evaluation of the velocity vector direction. This error becomes even larger if the hot-wire output signals are superposed by small measurement errors. In addition, *Roseman 1989* gives a detailed analysis of the uniqueness domain and angular sensitivity behaviour of a number of triple-wire configurations.

Triple probes are also designed in „T" geometry (fig. 1), consisting of an „V" probe and a third sensor inclined at 45^0 with respect to V-wires plane. Turbulence researchers apply such probes in order to simplify the signal interpretation procedure, see *Spencer 1970, Chang, Adrian and Jones 1983* etc. *Vukoslavčević, Balint and Wallace 1991* also applied „T" configuration as a part of nine-sensor vorticity probe. However, „T" geometry slightly reduces the uniqueness domain in comparison to orthogonal triple probes. *Vukoslavčević and Wallace 1983* found half-angle of uniqueness cone to be 26. 5^0 for ideal „T"-probe illustrated in fig. 1 (effective wire-cooling angles equal to geometrical $\alpha_E=\alpha_G=45^0$ and no aerodynamic blockage $k_B=1$). Unfortunately, the analysis of the real calibration data gave the value of only about 17. 5^0 for very small probes and low velocities. Similar results, originating from slightly different approach, were reported by *Petrović 1996*.

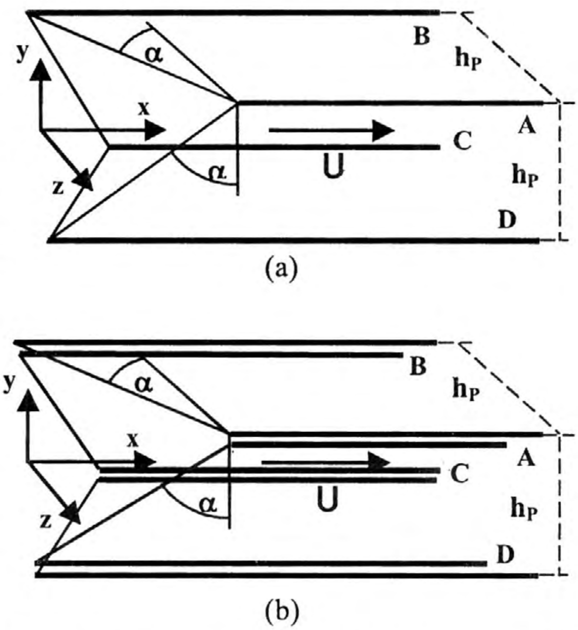


FIG. 10: Vorticity probes designed by *Kovasznay 1950* (a) and *Vukoslavčević and Wallace 1981* (b).

However, fast development of digital computers has highly increased their computation speed, enabling efficient application of very complex procedures for hot-wire output signals interpretation. From that point of view, simple interpretation algorithms for „T" configurations do not represent their advantage anymore and it seems that these probes are going to be rejected from the practical applications.

The second and presently the most promising approach in reducing the difficulties of interpreting triple-probe output voltages is to introduce the special four hot-wire probes in the operational practice. *Kovasznay 1950* and *Kovasznay 1954* designed the first quadruple probe (fig. 10(a)), quite independently from the analysis presented above. He specified this configuration for measurement of turbulent longitudinal velocity **U** and

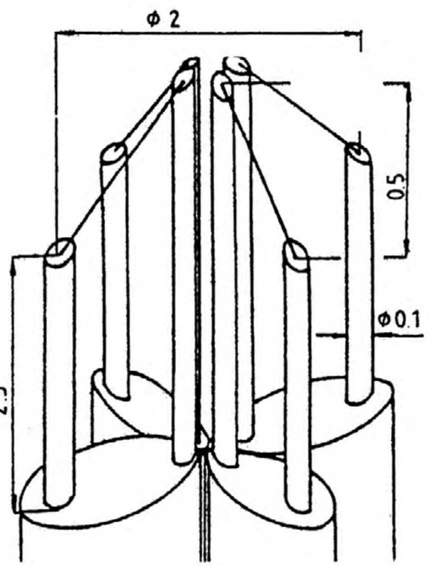


FIG. 11: The quadruple probe of *Dobbeling, Lenze and Leuckel 1990.*

vorticity ω_X, but it was not capable of measuring the other two velocity components **V** and **W**. *Vukoslavčević and Wallace 1981* practically finalised its design. They minimised probe dimensions (according to spatial criteria of *Wyngaard 1969*) and introduced separate (independent) prongs for each sensor (fig. 10(b)). This way the cross-talking between different wire-signals was eliminated and probe became capable of simultaneous measuring of all three velocity components. The tips of the prongs were bent according to recommendations of *Strohl and Comte-Bellot 1973* to reduce aerodynamic disturbances. However they showed that this probe was able to resolve the longitudinal vorticity only under severe restrictions due to the neglected velocity gradients. They were among the first who pointed out the strong influence of velocity gradients not only on vorticity but also on velocity measurements. This problem can be resolved by either minimizing of the probe dimensions or using nine or twelve-wire vorticity probes.

Lemonis and Dracos 1995 were the first who performed signal interpretation of a four-wire probe as a simple combination of four triple-sensor configurations. The velocity vector solution was obtained by averaging the four triple-wire solutions that are very close one to another. Ideally, they should be coincident. Quadruple probes have been also employed by *Phailas and Cousteix 1986*, *Samet and Einav 1987* (fig. 12), *Rose-*

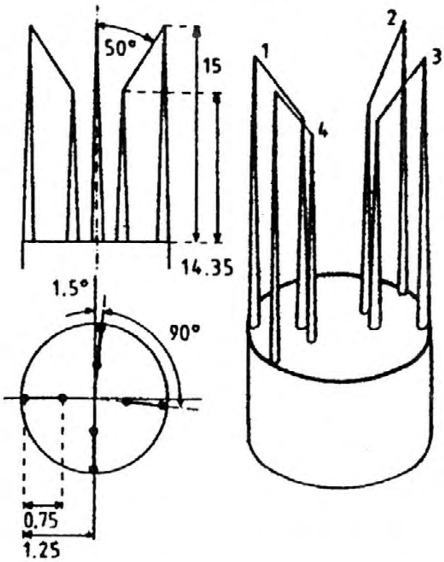


FIG. 12: Sensor arrangement of the probe of *Samet and Einav 1987.*

mann 1989, *Dobbeling, Lenze and Leuckel 1990a, b* (fig. 11), *Nguyen 1993*, *Marasli, Nguyen and Wallace 1993*, *Park and Wallace 1993*, *Pompeo and Thomann 1993*, *Vukoslavčević and Wallace 1996* (as a part of twelve-sensor probe), *Petrović and Vukoslavčević 1997*, *Vukoslavčević and Petrović 1997a, b* etc. *Phailas and Cousteix 1986* as well as *Rosemann 1989*, stated that uniqueness cone can be slightly enlarged by increasing the wire-angles toward the probe axis, which on the other hand reduces the probe angular resolution.

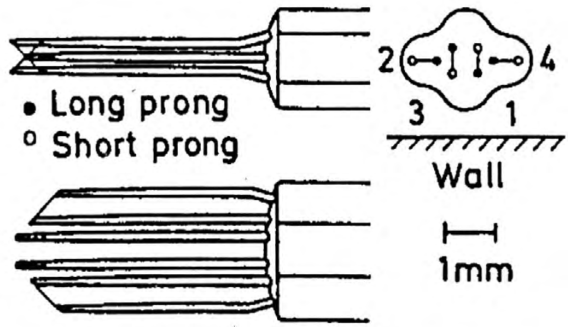


FIG. 13: The special four-wire probe, designed by *Pompeo and Thomann 1993*.

At present, a variety of procedures for signal interpretation of the four-wire probes exists. However, they can be classified in a very few general approaches.

Samet and Einav 1987, *Rosemann 1989* and *Pompeo and Thomann 1993* reduced the four-dimensional problem to two coupled two-dimensional problems. They are solved by iterative algorithm, such as two coupled X-wire probes. *Dobbeling, Lenze and Leuckel 1990a* indicated that this approach sometimes results in ambiguities. The interpretation procedures of *Dobbeling, Lenze and Leuckel 1990a, b* and *Marasli, Ngyen and Wallace 1993* overcame this problem by involving procedure that solves the resulting system of four wire-response non-algebraic equations using least-square minimization procedure.

All reported procedures for numerical support of the four-wire probes utilise simultaneously all four signals. The only exclusion is the algorithm of *Vukoslavčević 1994*, who involved a special sub-algorithm that chooses three (of four) output signals, which correspond to the sensors providing the best angular resolution for the instant orientation of fluid velocity vector. It was extended for 12-wire probe ***WP-12+(G)*** specified for vorticity measurements by *Vukoslavčević and Wallace 1996* and also used by *Vukoslavčević and Petrović 1998*.

Majority of designers of four-wire probes based their interpretation procedures on the average values of calibration coefficients obtained from probe directional calibrations performed in finite steps for several velocity magnitudes. Directional calibration involved probe oriented at all possible angles to be encountered in the measurement, at only one magnitude of calibration velocity. In place of using average values, the interpretation algorithms of *Dobbeling, Lenze and Leuckel 1990a, b*, *Park and Wallace 1993*, *Vukoslavčević 1994*, *Vukoslavčević and Wallace 1996* and *Ong and Wallace 1996* involved calibration coefficients from single-velocity directional calibration for each different velocity magnitude. These coefficients can be applied for hot-wire signals measured at each different location in the flow where the mean velocity is equal to the magnitude of calibration velocity. *Dobbeling, Lenze and Leuckel 1990a, b* assumed a model for sensor response equation, which allows de-coupling of velocity magnitude from its direction.

In order to improve directional sensitivity of hot-wire signals interpretation *Petrović 1996*, optimised the algorithm of *Vukoslavčević 1994*. This was achieved by taking into account the calibration coefficients velocity dependence not only on the mean but also on the instantaneous velocity magnitude at each measuring location. The idea originates from the algorithm of *Durst, Melling and Whitelaw 1970* for single-wire probe and procedure of *Petrović 1991* (also explained in *Petrović, Topisirović and Tošić 1997* and applied by *Petrović, Benišek and Oka 1997*) for X-probe. In addition, sensor-alternation subroutine of *Vukoslavčević 1994* was extended from two vertical on all four hot-wires of quadruple probe. Preliminary tests in the turbulent boundary layer flow, reported by *Petrović and Vukoslavčević 1997*, confirmed the superiority of optimised procedure (in comparison to the basic version of *Vukoslavčević 1994*) at low fluid velocities. However, as it was expected, both algorithms achieved similar results at higher velocity magnitudes.

Uniqueness cone of 40^0 half-angle corresponds to a maximum turbulence level of 38%, assuming the Gaussian distribution of isotropic velocity fluctuations and including 90% of all events (*Holzapfel, Lenze and Leuckel 1994*). Still, there exist many practical applications, which demands probes with larger acceptability range due to increased turbulence levels. A typical example of such situation is a turbulence velocity field measurement in a swirl flow with vortex breakdown. Using hot-wire anemometer in any flow of arbitrary configuration, the researcher has to carefully check that the acceptability range is not exceeded, neither by the calibration procedure nor during measurements. Almost all measured fluid velocity vectors have to be within the uniqueness cone, because even a few erroneous data points may significantly influence the measurement accuracy of higher moments statistics.

In order to additionally enlarge the uniqueness domain, *Holzapfel, Lenze and Leuckel 1994* constructed quintuple probe, sketched in fig. 14. It is composed of five hot-wires slanted at 45^0 toward the probe axis. They are evenly distributed in angles of 72^0 (90^0 is for the corresponding four-

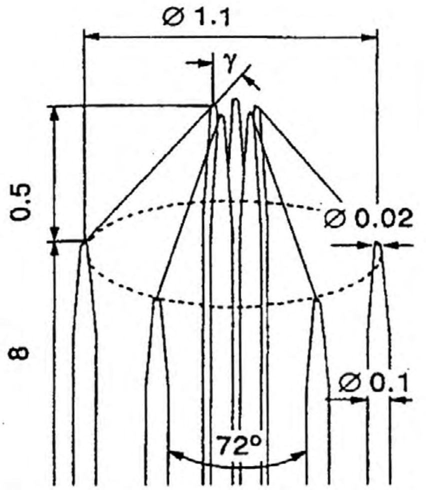


FIG. 14: The quintuple hot-wire probe of *Holzapfel, Lenze and Leuckel 1994.*

wire probe). This arrangement guarantees that at least four sensors are not in the wake of a prong, for any orientation of fluid velocity vector within a whole hemisphere. In addition, including the fifth wire into the probe arrangement provides at least three different output voltages for any flow direction within a hemisphere and therefore, as they believed, prevents ambiguities. They claim that under assumptions mentioned above, the velocity field measurement in a flow with a maximum turbulence level of 60. 6% can be made. However, available experimental set-up enabled probe calibration only within range of +/-70^0 for pitch and jaw angles. They did not give a straight forward proof of the uniqueness cone angle, so any assumption of achieving the uniqueness cone half angle higher then the hot wire angle toward probe axis, should be taken with extreme care.

6. INFLUENCE OF MULTI-WIRE PROBE DIMENSIONS AND CONFIGURATION ON MEASUREMENT ACCURACY AND UNIQUENESS DOMAIN

Finite dimensions of hot-wire probes sometimes can lead to errors induced by strong gradients of the velocity fluctuations and especially of the mean-velocity gradients in the probe sensing volume. This phenomenon has been in the focus of researcher's interest for many years, but has not been completely resolved yet. *Wyngaard 1969* reported important results, which are very often cited even nowadays. In order to resolve some problems connected with vorticity measurements, reported by *Vukoslavčević and Wallace 1981*, *Wassmann and Wallace 1979, 1980* proposed a new configuration of vorticity probe which should (besides all three velocity components) also enable measurements of velocity gradients. The proposed design, containing three arrays with three hot-wires, was developed by the new research team over a period of 10 years. *Balint, Vukoslavčević and Wallace 1987* and *Vukoslavčević, Balint and Wallace 1989* performed the first test-measurements of instant values of all three components of fluid vorticity vectors using preliminary versions of the nine-wire vorticity probe. Its final design was reported by *Vukoslavčević, Wallace and Balint 1991*. This was the first probe capable of simultaneous measurements of all three velocity components without neglecting neither any of velocity components nor the velocity gradients inside of measuring volume. Besides this team at the University of Maryland, a few other research-groups also used probes with nine or twelve hot-wires in various flow configurations (see *Tsinober, Kit and Dracos 1992*, *Honkan 1993* and *Park and Wallace 1993*). Finally, *Vukoslavčević and Wallace 1996* and *Vukoslavčević and Petrović 1998*, reported clear advantages of twelve-sensor probes in comparison to the configurations with nine hot-wires. They were the first who used a special algorithm, which takes into account the non-uniformity of velocity field not only between arrays but also within each individual array.

Due to the chosen probe geometry and its finite size, the particular wires sense different fluid velocities. Furthermore, each sensor averages the velocity over its finite length. Both the finite probe dimensions and finite length of its wires can in the worst case lead to complete misinterpretation and definitely alter the results of turbulent velocity field measurements, especially for higher-moments of velocity fluctuations (*Rosemann 1989* and *Pompeo and Thomann 1993*). To reduce this influence, designers try to minimise the probes, what is not always simply. Small dimensions sometimes cause thermal and aerodynamic interference of probe elements. Short sensors suffer from non-uniform temperature distribution over their length, because of end-conduction losses.

Following the criteria of *Wyngaard 1969* and knowing Kolmogorov scale, which describes the smallest turbulence coherent structures, most of existing four-wire probes seem to be fairly large for application in the turbulent flows. Diameter of measuring volume of the probe designed by *Dobbeling, Lenze and Leuckel 1990a, b* (fig. 11) is equal 2mm. *Samet and Einav 1987* (fig. 12) designed even larger configuration of 2. 5mm in diameter. To suppress the influence of mean velocity gradient normal to the wall, *Pompeo and Thomann 1993* constructed a special four-wire arrangement presented in fig. 13. They decreased vertical dimension of the probe measuring volume to only 0. 5mm. However, this design increased the probe width over 2mm, which is still fairly large (while the height of only 0. 5mm should be acceptable in well-designed wind tunnels and carefully chosen flow regimes). Unfortunately, all of these designers didn't provide reliable information about Kolmogorov microscale at relevant flow locations, preventing any possibility of estimating spatial resolution of their probes.

Fortunately, some other probe designers have constructed smaller probes. Typical examples, available at the University of Montenegro in

Podgorica, are presented in fig. 1: the probe ***VP-4+*** is 1mm in diameter and diameter of ***VP-4q*** is only 0.7mm. Both probes posses 2.5μm tungsten wires. At present, if thinner commercially available sensors would be used, current technology would enable further minimisation of their dimensions (even twice smaller probes can be manufactured). However, it seems that the newest quintuple probe of *Holzapfel, Lenze and Leuckel 1994*, specified for velocity field measurement, currently represents the best available choice for highly turbulent flows. This configuration provides the highest accuracy and the largest uniqueness domain, having the same dimension as four-sensor probe. Diameter of its measuring volume is only 1.1mm, with 2.5μm tungsten wires. Unfortunately, *Holzapfel, Lenze and Leuckel 1994* didn't provide information of possible further probe minimising, if thinner sensors would be used. The upper limit of uniqueness cone of this probe is also questionable.

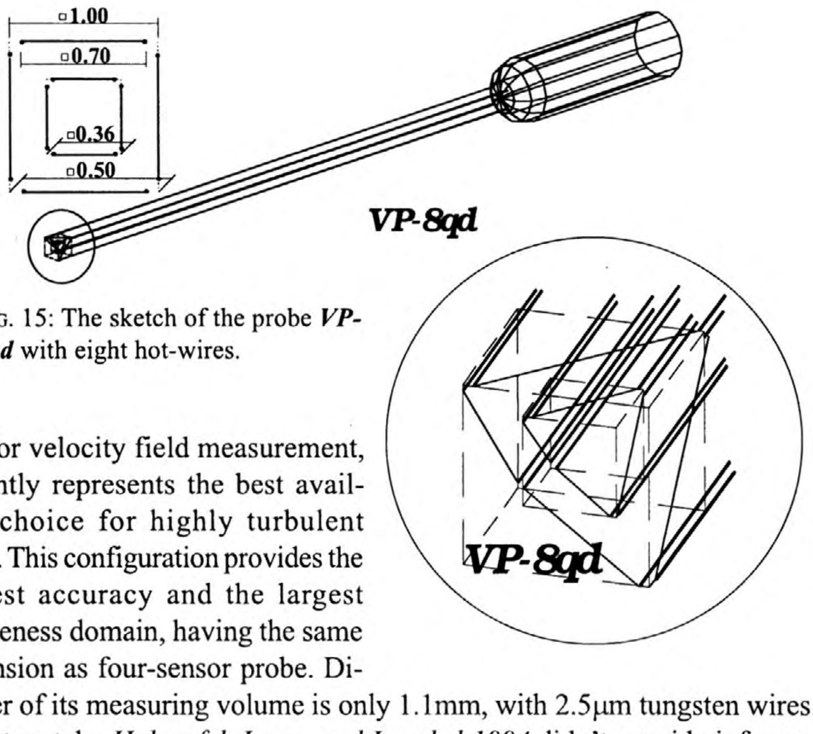


FIG. 15: The sketch of the probe ***VP-8qd*** with eight hot-wires.

An original probe ***VP-8qd*** (see fig. 15) for testing the influence of hot-wire probe dimensions on measurement results of turbulent velocity field was applied by *Petrović 1996* and *Vukoslavčević and Petrović 1996*. Dimensions of this miniature probe are shown in the left angle of fig. 15. The probe consists of two coaxial quadruple hot-wire arrays (see configuration ***VP-4q*** in fig. 1), placed one inside the other. Typical dimension of the smaller array is half the size of the outer one. This gives the four time smaller sensing area and eight times smaller the measuring volume of the inner array, in comparison to the outer. The criterion for estimating the influence of velocity gradients is very simple. If the results that correspond to both arrays are equal or differ within the desired limit, spatial resolution of the inner array is correct and measurement results should be accepted as reliable.

Both arrays of ***VP-8qd*** are very similar to modified type *Kovasznay 1954* probe, designed by *Vukoslavčević and Wallace 1981*. The sensors are positioned at angles 45^0 toward probe axis. Diameter of eight tungsten wires is 2.5μm. They are placed on stainless steel prongs, 0.25mm in diameter, tapered to about 40μm on their tips. The fabrication of the probe is similar to fabrication of the vorticity probe ***WP-12+(G)***. As it can be seen from fig. 15, the design of the probe ***VP-8qd*** enables simultaneous examination of the quadruple probe ***VP-4q***, as well as „X" probes in both vertical and horizontal plane ***VP-2x/V*** and ***VP-2x/H***.

Besides overall dimensions of the probe measuring volume, geometry also determines its operational characteristics. Among them, very important is the size of uniqueness domain and probe angular resolution. Although a whole variety of corresponding papers exists, it seems that the most illustrative are works of *Rosemann 1989* and *Lekakis, Adrian and Jones 1989*. They found the orthogonal geometry as an optimum for triple wire probes. It represents a compromise between the size of uniqueness domain and probe overall angular resolution. In addition, *Rosemann 1989* reported similar conclusion for four-wire probes, but at wire angle $\gamma=45^0$ toward the probe axis. The uniqueness domains of quadruple probes are generally larger than that of triple-wire probes, they are less affected by finite wire length and provide higher measurement accuracy of turbulence quantities than triples. Whether with three or four wires, sharper probes (with smaller angle γ – illustrated in fig. 14) exhibit a smaller uniqueness range and increased angular sensitivity toward changes of the flow direction. For a given value of the maximum turbulence intensity in the flow under investigation, the best probe should have the smallest wire angle γ, which still provides that all velocity vectors are within the uniqueness domain. This guideline allows the best angular sensitivity and enables uniqueness.

7. SUMMARY

A large variety of multiple hot-wire probes designed for three dimensional turbulent velocity field measurements are available today. None of them has universal applicability, so each experimentalist has to be very careful choosing the most convenient probe for a given type of turbulent flow. However, besides the probes designed for velocity measurements, some of the vorticity configurations (presented here) can be also applied for turbulent velocity measurement. Although designed primarily for vorticity measurement, they can also provide the highest measurement precision of turbulent velocity field, thanks to possibility to take into account the influence of instant velocity gradients within their measuring volume. They

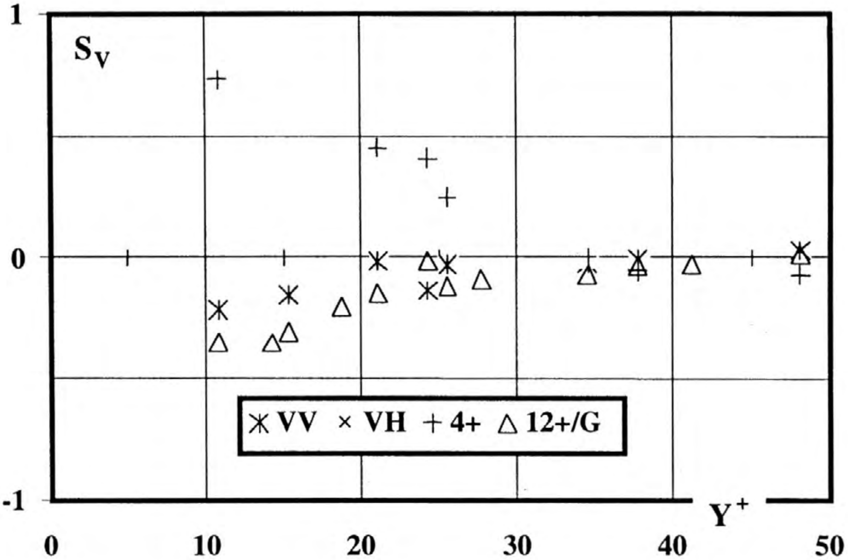


FIG. 16: Skewness **S** factors of transversal **V** turbulent velocity fluctuations distributions in the boundary layer, measured by various hot-wire probes (*Vukoslavčević and Petrović 1997*):

(a) VV - "V" probe positioned in the vertical plane;
(b) VH - "V" probe in the horizontal plane;
(c) 4+ - "+""probe *VP-4+* with four hot-wires and
(d) 12+G - ***WP-12+(G)*** probe, which takes into account the velocity gradients.

are also convenient to make comparison of measuring accuracy of different multiple hot wire probes, in order to analyse the influence of neglected fluid velocity or gradients components, as it is shown in figs. 16 and 17.

However, the vorticity probes are extremely complex and therefore very expensive and sensitive to mechanical and aerodynamic schoks. In addition, they demand sophisticated calibration procedures and signals interpretation algorithms. Follows that these probes should be manipulated by well-trained persons and supported with electronic equipment containing large number of measuring channels. These reasons cause the vorticity

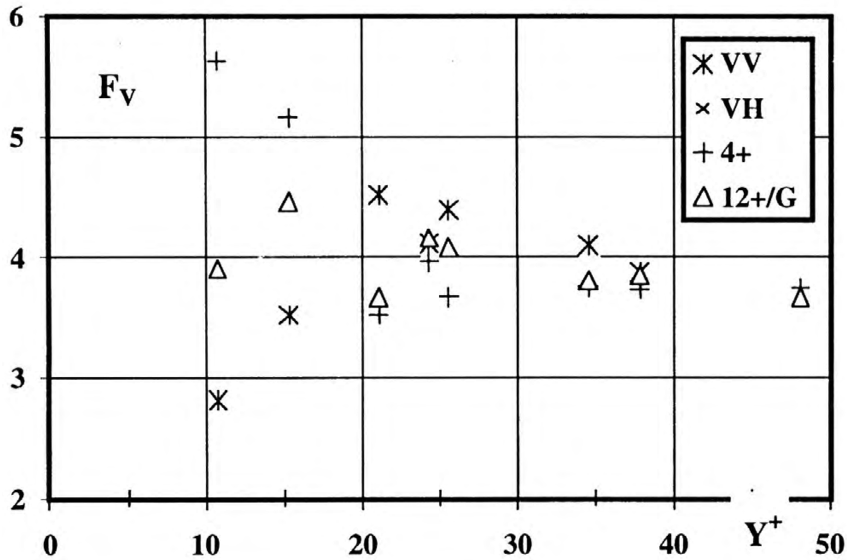


Fig. 17: Flatness **F** factors of transversal **V** turbulent velocity fluctuations distributions in the boundary layer, measured by various hot-wire probs by *Vukoslavčević and Petrović 1997*. For legend see fig. 16.

probes to be employed very rarely, and exclusively in the leading world aerodynamic laboratories. As known by the authors of present paper, they have never been employed for clear turbulent velocity measurements, but only in the situations involving the vorticity and/or velocity gradient measurements.

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