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ON THE DEVELOPMENT OF THE VORTICITY HOT WIRE PROBES

Abstract

The development of the hot-wire vorticity probes, since the appearance of the first one- component vorticity meter till the most sophisticated multi-sensor probes, is presented. This process can be described as a series of efforts aimed to improve the probes capabilities and accuracy. It was a complex process, viewed as an elusive goal of turbulence researcher over a long period. It required sophisticated optimization methods in order to avoid worsening one or more by improving the other parameters. The DNS (direct numerical simulation) database had and still have a great role in optimization of the probe size and geometry (number and position of the arrays and sensors) and uniqueness range. As a result of these efforts, we have probes that can reliably measure the cross-stream velocity gradients, necessary to define the vorticity components, with sufficient spatial resolution at least in laboratory conditions. Unfortunately, we still do not have a probe capable of the streamwise velocity gradients measurement with sufficient accuracy. Probes designed for that porpoise still have unacceptable measurement error in the near wall regions of turbulent flows. Besides the great results in the probe geometry improvement and various designs, presented in this paper, there is still a number of technical parameters like sensor temperature, flow blockade, frequency response and fabrication methods that should be optimized.

Keywords: multi-array hot-wire probes, vorticity measurements, virtual experiments, velocity gradient measurements, probe configurations, spatial resolution

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1. INTRODUCTION

Vorticity is a measure of the rotation motion of a fluid particle. It is a defining property of turbulence that characterize almost all fluid flows of technical interest. The presence of vorticity is assumed essential to identifying them as truly turbulent motions. Having in mind that a fluid particle can simultaneously rotate and deform the vorticity is defined as a mean angular velocity of the all axes passing through the center of a fluid particle. There could exist three vorticity components describing the rotation around all three Cartesian coordinate axes:

$$\omega_x = \frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z},\ \omega_y = \frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x},\ \omega_z = \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}. \tag{1.1}$$

There is a great advantage to describe the dynamics of turbulent motion in terms of vorticity. This is the possibility to express the equation of motion of turbulent flow particles in vorticity form:

$$\frac{\partial \omega_i}{\partial t} + u_j \frac{\partial \omega_i}{\partial x_j} = \omega_j \frac{\partial u_i}{\partial x_j} + \nu \frac{\partial^2 \omega_i}{\partial x_j \partial x_j}. \tag{1.2}$$

For the difference from the Navier Stokes equations, this form does not directly include the fluid pressure, which allows great simplifications in interpretation as well as in experimental and computational determination of fluid motion.

2. VORTICITY COMPONENTS MEASUREMENTS

In order to measure vorticity two basics method have been developed; thermal anemometry and optical anemometry. The first attempt to measure the ω_x vorticity component using thermal anemometry was made about 70 years ago. It took about 40 years to develop reliable vorticity probe capable to simultaneously measure all three vorticity components. The first successful results using optical methods were obtained about 30 years ago. Both methods are rather complex requiring very expensive equipment to collect and process the experimental data. Wallace and Vukoslavčević (2010) give an interesting presentation of these methods. Both methods are still under investigation in order to improve their characteristics, accuracy and possibilities to be applied in various fluids and practical conditions. Having that in mind, a historical review of their development with the emphasizes on the encountered problems and the approaches of their resolving, could be of great interest to the further improvements of these methods. This paper is devoted to the the thermal anemometry method only.

It is clear from the expression (1) that in order to determine vorticity components experimentally the velocity gradients should be measure. To measure velocity gradients in a given direction, the velocity components has to be measured in two points separated in that direction by a distance of the same order as the smallest structure that can be expected in the turbulent flow. The size if these structures define the probe spatial resolution. Having in mind that these structures are of the order of the Kolmogorov microscale η defined by Kolmogorov (1941), it was clear from the very beginning that constructing of a probe capable of resolving the smallest turbulent structures was an elusive goal even in laboratory conditions. The researchers have aimed their efforts to construct the probes as small as possible. The minimal probe dimensions were limited by the sensors and prongs dimensions as well as the mutual sensor thermal contamination and flow blockade by its presence. The construction techniques and skills has been developed over time, so today is possible to built the probe capable to resolve up to 80% of the existing turbulent structure, at least in laboratory conditions.

3. KOVASZNAY TYPE VORTICITY PROBE

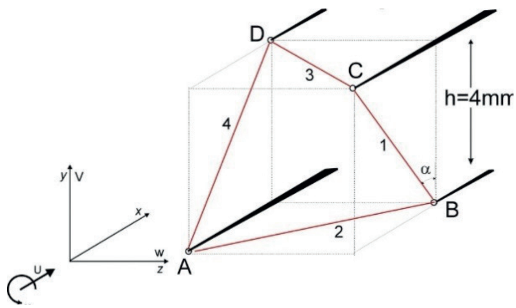


Fig.1. Sketch of Kovasznay-type vorticity probe

Kovasznay (1950), (1954) proposed the first probe capable of streamwise vorticity and velocity components measurements. The probe consists of four hot wire sensors and four prongs, Fig.1. Each support prong is common for two sensors. It was believed that, under some assumptions, the streamwise vorticity component should be a function of voltage difference between points A and C and streamwise velocity component a function of the voltage difference between the points B and D:

$$\omega_x = F\left(E_A - E_C\right);\ U = F\left(E_B - E_D\right). \qquad (2.1)$$

These functions should be determined in a calibration procedure. The necessary assumptions has been discussed in details by Vukoslavčević and Wallace (1981).

They found out that, in order to form the expressions (2.1), the following conditions has to be satisfied:

$$h\frac{\partial v}{\partial y} << v_0,\ \ h\frac{\partial w}{\partial z} << w_0,\ \ \frac{w_0}{U_0} << 1,\ \ \frac{v_0}{U_0} << 1, \tag{2.2}$$

where U_0, v_0 and w_0 are the velocity components at the probe center. Besides, the probe should bi built as symmetrical as possible, with the same length and sensor inclination α for each sensor. A linear sensor voltage response to the velocity magnitude should be assumed too.

It is clear that he first of the two conditions (2.2) will be valid only if the sensor separation *h* is mall enough or, in other word, if the probe has sufficient spatial resolution. Wingard (1969) has analyzed the response of the Kovasznay's vorticity probe. He fond out that *η/h*, where *η* is the Kolmogorov microscale, should be greater than 0.3 for the ratio of the wire lengths to the spacing between wires *h* being close to 1.0. The other two conditions cannot be satisfied in the near wall region of the flow. This region, known as the boundary layer, is present in the most of the flows of practical interest. The probe was used infrequently in the next 30 years due to the technical difficulties in construction to make it small enough to satisfy the spatial resolution. It also requires a rather complex and expensive calibration mechanism. It has been used by Uberoi and Corsin (1951), Kistler (1952) and Kastrinakis, Eckelmann and Wilmarth (1979). They found out that insufficient probe spatial resolution and the influence of *v* and *w* velocity components can create a significant measurement error. They also suggested that a way around his problem is in constructing a probe with each sensor supported by separate pair of prongs. This means to use a probe of the same configurations but with eight in place of four prongs. Each sensor should be operated separately. That way, the probe should be capable to measure not only the streamwise vorticity and velocity components but also the span wise velocity components *v* and *w*. With known values for *v* and *w* velocity components, their influence on the streamwise vorticity components could be corrected. They also emphasized that such a probe will be much more difficult to built and satisfy the spatial resolution, than in the case of the original version.

4. THE MODIFIED VERSION OF THE KOVASZNAY'S TYPE VORTICITY PROBE

Vukoslavčević and Wallace (1981) perform the first detailed analysis of the influence of the spanwise velocity components v and w on the accuracy of the streamwise vorticity component measured by a modified version of the Kovasznay-type vorticity probe. A schematic drawing of this probe is shown in

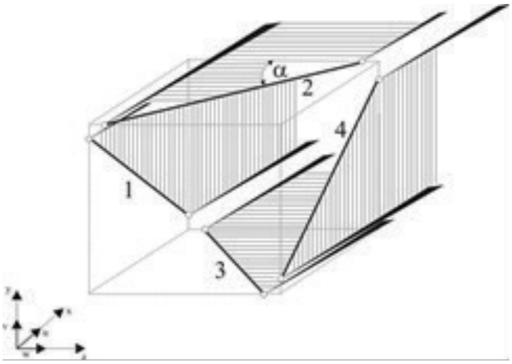


Fig.2 Sketch of modified Kovasznay-type vorticity probe

Fig.2. The probe consist of four pair of prongs and four sensors. For the difference from the Kovasznay-type probe, each sensor is supprted with a separate pair of prongs. This way twoo pair of X-wire probes are formed; one in vertical plain with sensors **1** and **4** and the other in horisontal plane, with sensors **2** and **3**. Such probes are, under ussul assumptions, capable of measuring all thre velocity components, what should give a posibility to correct tne influence of the spanwise velocity components on the accuracy of the streamwise vorticity component measurements.

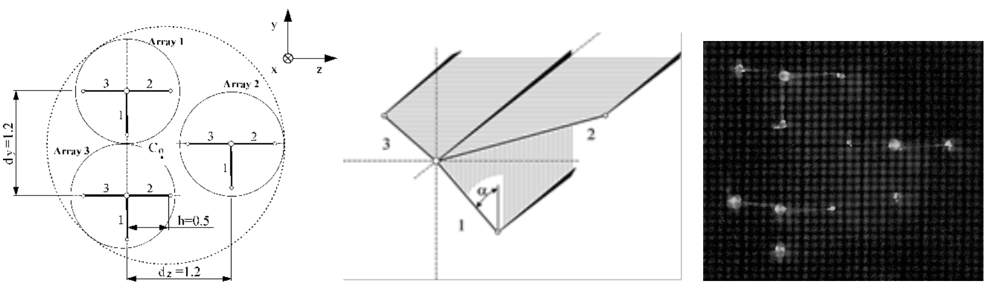
The dimensions of the probe were chosen to meet the spatial resolution criterion proposed by Wyngaard (1969). The wire lengths are $l\approx 0.72$ mm and the distances between the planes containing the oposite wires are also $h\approx 0.72$ mm. For the low speed boundary layer flow, where the probe was tested, the Kolmogorow microscale was $\eta\approx 0.4$ mm at $y^+=15$. The ratio of the wire length to the spacong between wires is $l/h=1.0$ and the ratio of Kolmogorow microscale to the wire distances is $\eta/l\approx 0.55$, well above the minimum value of 0.3 proposed by Wyngaard. Despite the more complex probe geometry, in comparison to the original version of the Kovasznay's type probe, the dimensions of this probe were about five times smaller than any of the previously constructed Kovasznay-type probes.

They proved that this probe can account for the influence of the streamwise velocity component to the streamwise vorticity measurement under a common assumption that these velocity components can be reliably measured with a pair of X-array wires. It is well known that this assumption is correct only if the streamwise velocity incriments $h\partial U/\partial y$ and $h\partial U/\partial z$ are much smaller than U. This can be achieved by reducing the spacing h betwen the plane cantaining the wires. Unfortunately, the spacing between the horizontal wires is limited by the length of vertical wires and vice versa. They studied the influence of $\partial U/\partial y$ and $\partial U/\partial z$ gradients by measuring their mean and maximal instantenous values. They have proven hat the streamwise vorticity component can be badly in error whether the effect of cross-stream velocity compnents v and w are accounted for or not. When they are accounted for, the error over 30% in the near wall region apperas due to the neglection of the streamwise velocity gradients. The final conclusion was that all six velocity gradients: $\partial U/\partial y$, $\partial U/\partial z$,

$\partial v / \partial y, \partial v / \partial z, \partial w / \partial y$ as well as all three velocity components have to be measured simultabeously. They proposed the construction of a nine sensor probe, having the same number of sensors as the number of the unknowns to be maesured.

5. THE NINE SENSOR HOT-WIRE VORTICITY PROBE

The first probe capable of reliable simultaneous measurements of all three vorticity components is constructed by Vukoslavčević et al (1991), and the first measurements and statistical analysis of the velocity and vorticity fields is performed by Balint et al (1991). The probe is shown in Fig.3.



(a) (b) (c)

Fig.3 Nine sensor probe to measure simultaneously v_x, v_y, v_z and ω_x, ω_y, ω_z : (a) end-view sketch, (b) schematic view of one of its three-sensor arrays, (c) photograph of the probe

The construction of the probe started in 1979. It took more than 10 years to develop it to full operational capability. Progress reports on its development and partially successful measurements has been presented by Wassman and Wallace (1979), Vukoslavčević and Wallace (1984), Balint et al. (1987), Vukoslavčević et al. (1989) and Balint et al. (1990).

The probe consist of three arrays spaced 1.2 mm in *y* and *z* directions. Each array consists of two sensors forming a V shape in *x-z* plane and a third sensor at 45° in the orthogonal *x-y* plane. In order to achieve better space resolution, this probe has a common prong in the center of each array. To avoid the electrical cross talk between the circuits it was necessary to reduce the common prong resistance below 0.1 ohms. As an optimal value, the overheat ratio was chosen to be 1.2. A higher overheat ratio will cause the sensor thermal contaminations and the lower one will affect the probe sensitivity. The probe is quite compact with the largest sensing dimension of 2.2 mm, as it can be seen in Fig.3 (c) and sketch of Fig.3 (a). The average distance between sensor centers over which the velocity gradient were estimated is about 6.3η at y^+=15, decreasing to 3.7η at y^+=183 in the boundary layer of Balint et al (1991).

The effective velocity cooling each sensor are expressed in function of normal, tangential and binormal velocity component acting to each sensor as proposed by Jorgensen (1971). The functional form of these expressions, for the *j-th* sensor *of i-th* array are,

$$U_{eij}^2 = F(a_{ijk}, U_{ij}, V_{ij}, W_{ij}) \tag{5.1}$$

The velocity components at each sensor center can be expressed as a function of the velocity components at the probe center, U_0, V_0 and W_0, and velocity gradients in the cross-stream *y* and *z*-directions,

$$U_{eij}^2 = F_{ij}\left\{a_{ijk}, U_0, V_0, W_0, \partial\left(U,V,W\right)/\partial y, \partial\left(U,V,W\right)/\partial z\right\}. \tag{5.2}$$

This way nine algebraic nonlinear equation with three velocity components and six velocity gradients unknown are formed. The 27 a_{ijk} coefficients are determined from the probe calibration procedure. The form of the expression (5.1) depend on the various versions of the cooling law. In a case of the nine-sensor probe, the influence of tangential cooling velocity is taken into account by the concept of an effective sensor angle introduced by Bradshaw (1975) and used by Bruun and Tropea (1980).

A specific numerical algorithm is developed to solve these equations. One of the problem encountered was the uniqueness range of the obtained solution. They found out that each of the sensor array has a cone acceptance of about 20^0. This means that if the resulting velocity vector forms an angle with *x*-axes higher than 20^0 the solution cannot be unequally determined. This is usually not the case in the boundary layer flows except very close to the wall.

The statistical properties of turbulent boundary layer, measured by this probe, are reported by Balint et al (1991). Having in mind that this type of probes cannot measure the streamwise velocity gradients, these gradients were estimated using Taylor's hypothesis (1938). This hypothesis, in its simplest form, is given by the expression,

$$\frac{\partial U_i}{\partial x} = -\frac{1}{U_c}\frac{\partial U_i}{\partial t}, \tag{5.3}$$

where U_c is the convective velocity, taken usually as the streamwise velocity component or its mean value. Several authors have questioned the validity of

Taylor's hypothesis in a flow with large mean gradients. Piomelli et al (1989) have investigated this hypothesis using a well resolved numerical simulation of turbulent channel flow. They found out that the correlation of the gradient $\partial U_i / \partial x$ determined from numerical simulation and Taylor's hypothesis is quite high, above 0.9 for y^+>20. Besides Balint et al (1991), this probe has been used by Ong (1992) and Wallace et al (1992).

Honkan (1993) and Honkan and Andreopoulos (1993) implemented several improvements to the design of the Vukoslavčević et al (1991) probe. First, the sensor in each array are rotated 120^0 in the cross-stream plane, Fig.4. This configuration increases the uniqueness range to about 30^0. As is discussed by Vukoslavčević et al (2004), the maximum value of the uniqueness cone for this configuration is 35.26^0. Second, each sensor is supported by a pair of separate prongs, that way eleiminated any possibility of cross talk between the senors. As a consequences the spatial resolution of this configuration was twice vorse than in the previous one. They also used a calibration procedure with simultaneous pitch and yaw variation. This approach should provides a better representation of turbulent flow fields in comparison to separate pitch and yaw as it was done by Vukoslavčević et al (1991). In the data algorithm mechansam the velocity was assumed to be constant over the array sensing area and vary only between the arrays.This was an other disandvantage in comparison to Vukoslavčević et al (1991) approach, where the velocity linear variation over the whole sensing area was assumed.

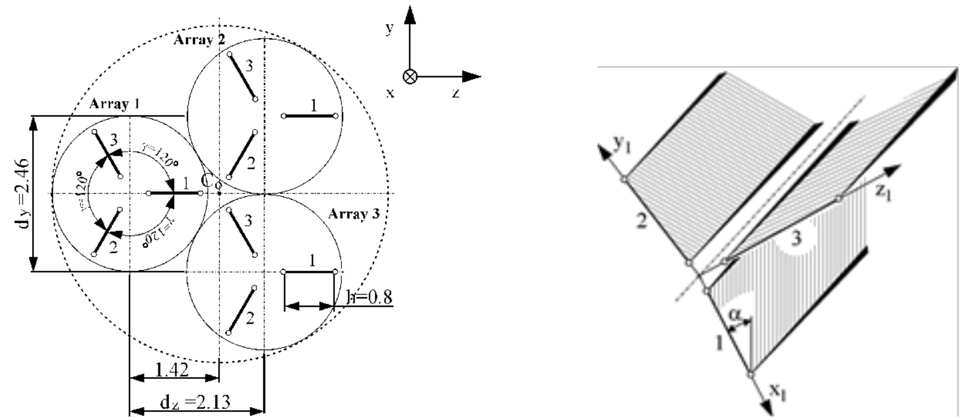


Fig.4 Sketch of the nine-sensor orthogonal configuration probe (b).

6. TWELVE SENSOR HOT WIRE VORTICITY PROBES

Studding the uniqueness range of the nine-sensor vorticity probe of Vukoslavčević et al. (1991), they found out that the uniqueness range is strongly atenuated if the *v* velocity component is positive. A function *F(v),* shown in Fig.5, can be obtained in an iterative procedure for each array of nine sensor probe, shown in Fig.3, by eliminating the *u* and *w* velocity components from the three of the equations (5.1).

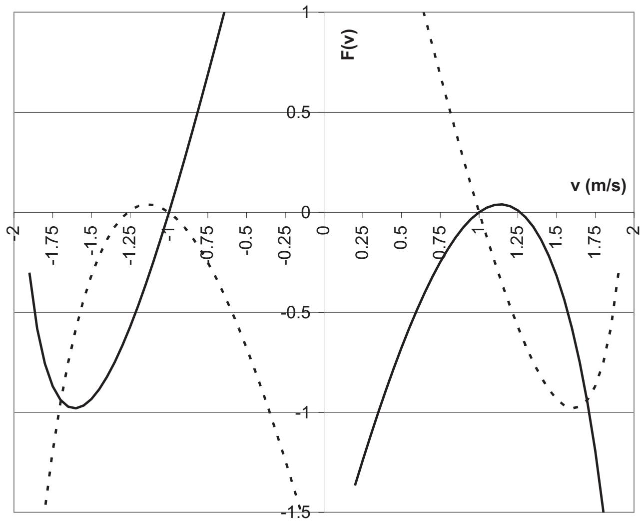
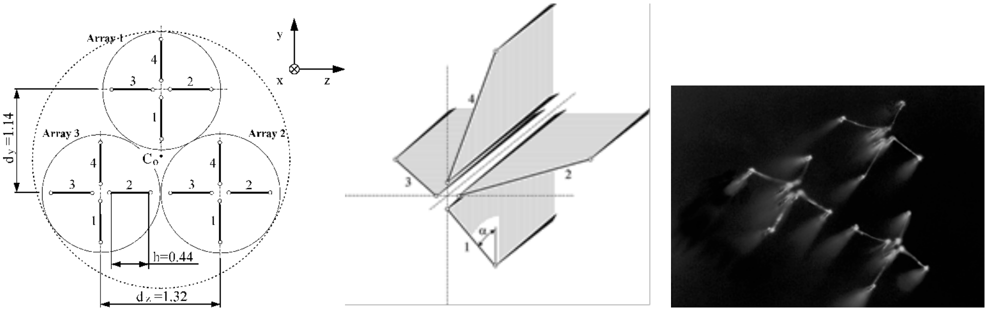


Fig.5 Function *F(v)* curves for various *v/U* ratios and *w* nearly zero: (−) the combination with sensor **1** below sensors **2** and **3**; (- -) the combination with sensor **1** above sensors **2** and **3**

The intersection of this function with abscissa define the value of *v*-velocity component. For the case with sensor **1** below sensors **2** and **3**, as shown in Fig.3, there is only one intersection of this curve with abscissa in the region of $v<0$, giving a unique solution for *v*, as seen in Fig.5. For $v>0$ there are two solutions one always smaller and the other bigger then a critical value, v_{cr}, defined by the point where the curve *F(v),* is touching the abscissa. This critical value defined the uniqueness range. If we know in advance that *v* is always smaller than v_{cr} we can chose the smaller of the two obtained solutions. Otherwise, it is impossible to distinguish which of the two solutions really exists in a flow. It was clear that if the sensor **1** is placed above sensors **2** and **3**, the uniqueness range problem will shift in the range $v<0$ (the dashed lines in Fig.5). Keeping the sensor **1** below sensors **2** and **3** and adding an additional sensor above sensors **2** and **3**, forming that way a four-sensor array, it is always possible to choose the appropriate sensor, depending on the sign of v value component, and that way reduce the problem of uniqueness range to a great extent. As it was found later by Vukoslavčević et al (2004) a theoretical upper limit of the uniquenss cone, defined by the ratio of spanwise and streamwise velocity components, in this case is 39.2^0, for the sensor inclination angle of $\alpha=45^0$. Having that in mind, they started to develop a twelve-sensor probe, with four sensors in each of the three arrays.

The probe was used first by Nguyen (1993) and Marasli et al. (1993). The probe design and signal data reduction procedure are explained in detail by Vukoslavčević and Wallace (1996). The sketch of the probe is shown in Fig.6 (a) and Fig.6 (b) and its photograph in Fig.6 (c).



(a) (b) (c)

Fig. 6 (a) Sketch of the front view of a twelve-sensor probe, (b) schematic view of one of its four-sensor arrays, (c) photograph of the twelve-sensor probe

The array separation in this probe was 1.14 mm in the y-direction and 1.32 mm in the z-direction. The distance between the supporting prongs of each sensor, inclined at 45^0 to the probe axis, was 0.44 mm with a sensing area of 2.2 mm in y-direction and 2.4 mm in z-direction. The diameter of the tungsten sensors was 2.5 μm and their length was about 0.62 mm, giving an aspect ratio of about 250.

The 12-sensor hot-wire vorticity probe was also constructed by Tsinober et al (1992). Their probe is shown in Fig.7.

Their motivation to add the fourth sensor was not the enlargement of the uniqueness range. It was related to the data reduction mechanism. They made four combinations of three sensors for each array, find the appropriate solutions and took the average value of each velocity component. That way they did not utilize the full extent of the uniqueness range that can be achieved by this probe. They also assumed that the velocity gradients were constant over each of the three arrays of four sensors and vary only between the arrays, like Honkan et al (1993) did. Having in mind that the ratio of the sensor sensing dimension and array separations are of the same order, this approach is questionable.

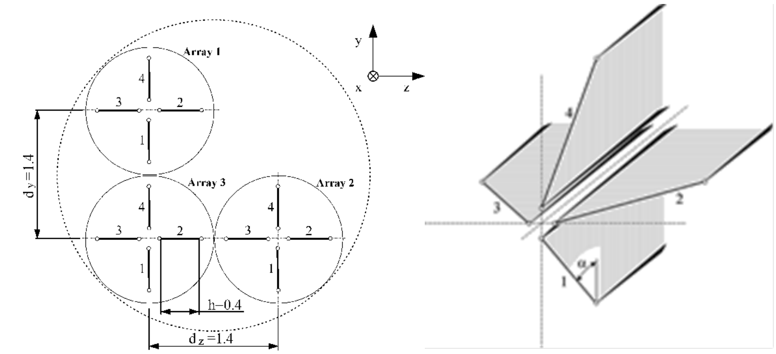


Fig. 7 Sketch of the front view of a twelve-sensor probe and schematic view of one of its four-sensor arrays

7. OPTIMIZATION OF THE HOT WIRE VORTICITY PROBES

A number of various probe size and configurations have been used so far in order to measure vorticity components in turbulent flows. Typical array configurations are shown in Fig.8.

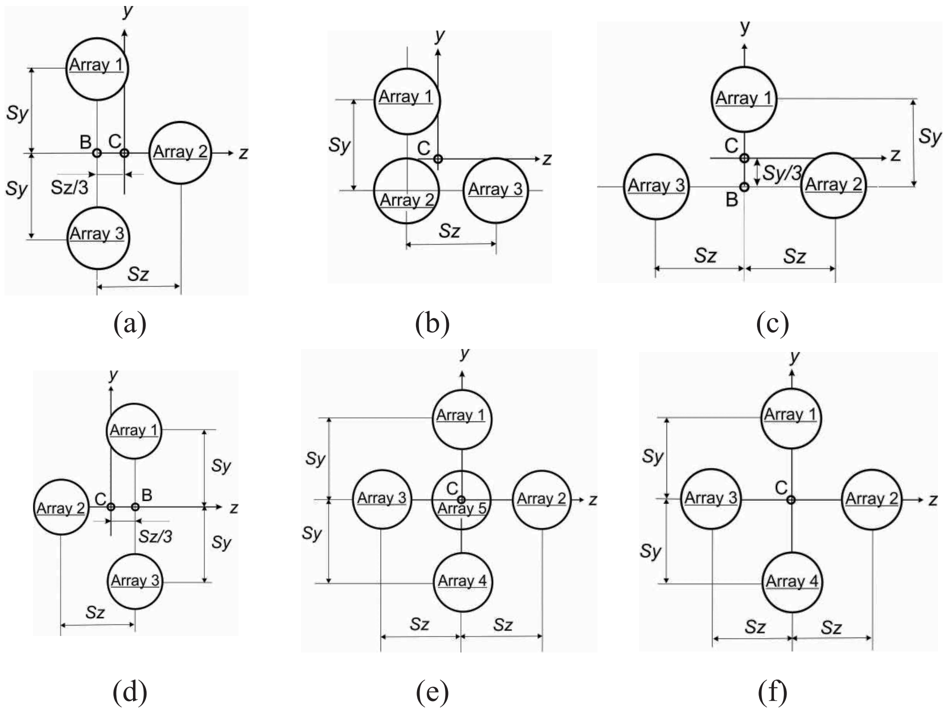


Fig. 8 Various array configurations of multi-sensor hot-wire probes:
(a) VWB3, (b) TKD3, (c) VW3, (d) HA3, (e) TKD5, (f) TKD4

A set of convenient abbreviations, is used here to label the various configurations. These set of abbreviations is introduced by Vukoslavčević and Wallace (2013). They consist of the first letters of the names of authors who designed and used them and the number of the arrays for each probe. The configuration VWB3 was used by Vukoslavčević et al. (1991), configurations TKD3 and TKD5 by Tsinober et al. (1992), VW3 by Vukoslavčević and Wallace (1996) and HA3 by Honkan and Andreopoulos (1997). Configuration TKD5, with the central array moved upstream of the other four arrays, was used by Galanty et al. (2003) and by Gulitski et al. (2007). Configuration TKD4 was used as a part of the TKD5 configuration.

There are a great number of parameters that can influence the accuracy of the vorticity measurements. These are: the array configurations, the sensor arrangements within an array and the ratio of the array and array separation size. All these parameters can be assigned as the geometrical configurations probe parameters. Besides these parameters the important influence on the measurements accuracy have the probe dimensions or probe spatial resolutions of a given geometrical configuration. Finally, a number of parameters set by electronics or anemometers boards, like overheat ratio of the sensors and their frequency response have also a great role on the measurements accuracy. The optimization of these parameters is a complex task. The simplest approach is to analyze the influence of each of them separately by varying it while keeping the other one constant. Unfortunately, many of these parameters influence each other so a simultaneous analysis of two or more of them is also necessary.

7.1 The influence of the geometrical configurations

In order to test the probe measurements accuracy and optimize its geometrical arrangements it will be necessary to place the probe in a turbulent flow of the known velocity field at each point in space and time and compared the measured values with the known (induced) one. Unfortunately, it is impossible to create such a turbulent flow with known velocity field as a function of space and time because the turbulence is a strongly stochastic process. In place of a real, a virtual experiment can be performed using the DNS (direct numerical simulation) of turbulent flows that are available since the work of Spalart (1988).

As discussed by Vukoslavčević and Wallace (2013), in order to eliminate all problems related to the sensor response and array characteristics (such as sensor dimensions, overheat ratio, thermal cross-talk between sensors within an array, disturbance of the flow by the presence of sensors and prongs, number and sensor’s orientations, uniqueness range) and study the effects of the array arrangements (positions and separations), one can imagine a perfect array that can precisely measure all three velocity components at its center. This can be any of the sensors arrays with ideal sensor response and array dimensions small enough to neglect the velocity variation over the array sensing area. The perfect arrays can be thought of as points arranged in the appropriate probe geometry and located on the mesh of a DNS. The relative positions of these points, for a specific configuration defined by the distances S_y and S_z from the probe center C to the array centers, are specified in Fig. 8. The velocity components values, measured by these perfect arrays, are the DNS values computed at these points.

A highly resolved DNS database of turbulent channel flow with a Reynolds number of $Re_\tau = 200$, where $\mathrm{Re}_t = u_\tau h/\nu$, u_τ is the friction velocity and h is the channel half-width, created by Piomelli et al. (2000), is used for this analysis. The first use of this database for this type of study was by Vukoslavčević et al. (2009). The size of the computational domain was set to 2h × 2h × h and was discretized using 400 × 400 × 200 grid nodes in the streamwise, wall normal and spanwise directions, respectively. The grid was uniform in all directions, and the resulting resolution is $\Delta x^+ = \Delta y^+ = \Delta z^+ \approx 1$, where "+" denotes normalization with the viscous length ν/u_τ. Near the wall, the grid size is almost 1.5 times smaller in each coordinate direction than the Kolmogorov length.

In order to study the geometrical arrangements only, the same spatial resolution of $S_y^+ = S_z^+ = 4$, $\Delta^+ = 1$ is taken for all array configurations shown in Fig.8. This resolution is sufficient to place any of the sensor configuration within an array with prong separation of $b^+ = 2$. This resolution is slightly better in the *y-direction* and much better in *z-direction* than the best spatial resolution of any of the experiments performed with vorticity probes so far. For the DNS of Piomelli et al. (2000) channel flow the ratio of the Kolmogorow microscale and array separation is $\eta / \Delta \approx 1.6$ at $y^+ = 15$, which gives $S_y / \eta = S_z / \eta = 2.5$, and maximum separation of the array centers about 5η. These values increase closer to the wall and decrease toward the channel centerline. Maximum array separation of the **VWB3** probe in the experiment of Balint et al (1991) was 6.3η in both directions.

Due to the dimension of the central array of the "TKD5" configuration, given in Fig.8, the distance from the probe to the arrays centers has to be slightly increased in this case depending on the sensor configuration within an array. An average value of $S_y^+ = 5.2\,\Delta^+ = 5.2$ should be sufficient for the most arrays used so far.

The effects of the array configurations on the vorticity component rms values, shown in Fig. 9, are presented by Vukoslavčević and Wallace (2013).

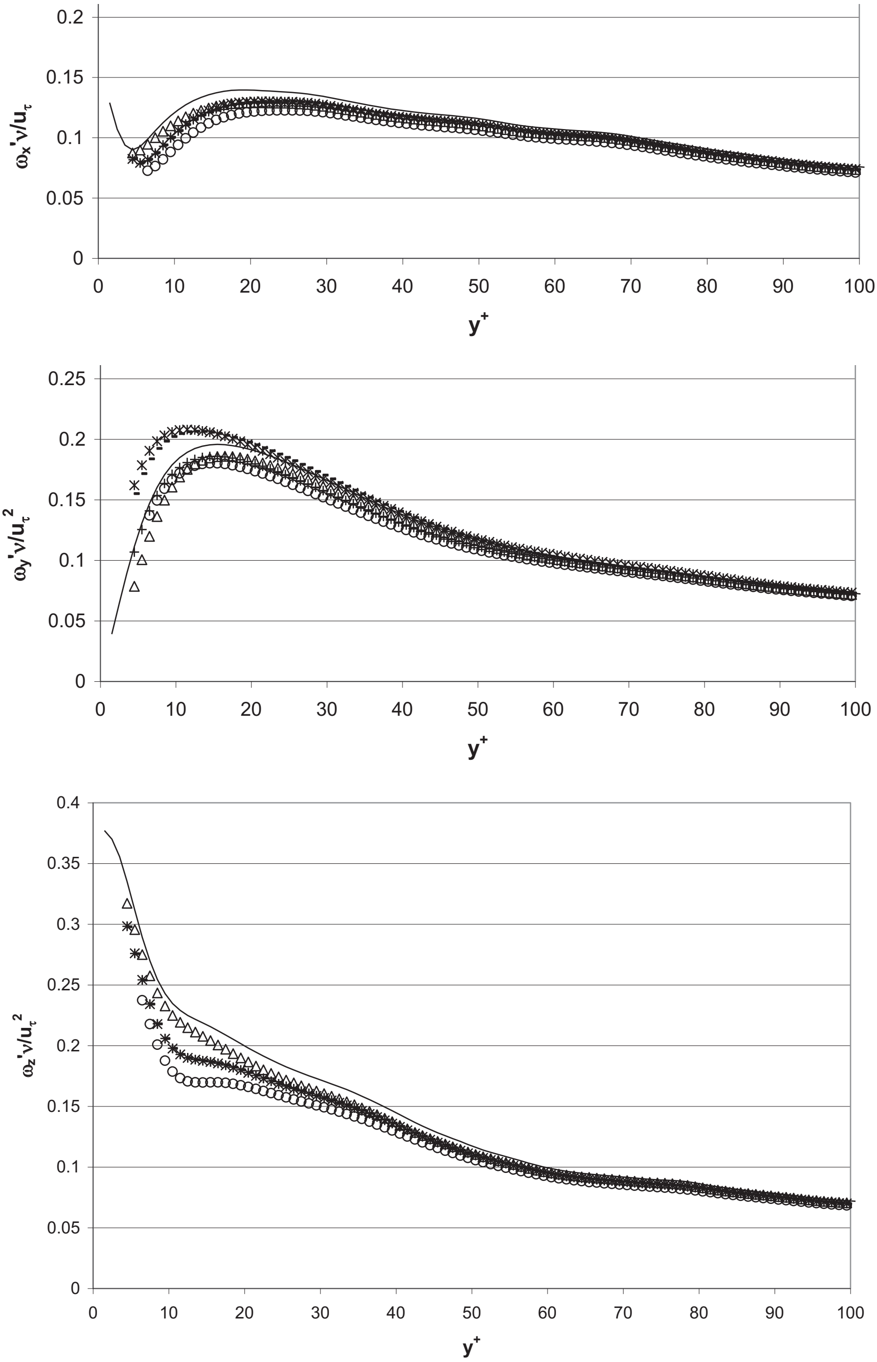


Fig. 9 Effects of the array configurations on the vorticity component rms values: *Solid line* DNS, *triangle* VW3, *dash* VWB3, *plus* TKD4, *star* HA3, all with $S_y^+ = S_z^+ = 4$; *circle* TKD5 with $S_y^+ = S_z^+ = 5.2$.

The rms accuracy of ω_x and ω_z is the best for **VW3** configuration due to the best resolution in *y* direction. The accuracy of the rms of ω_y is in large error for the **VWB3** and **HA3** configurations while it is close for the other configurations. The **VW3** configuration is also superior in the measurements of the skewness and flatness factor of vorticity components in comparison with the other configurations.

7.2 The influence of the probe spatial resolution

The assumption of linear velocity variation over the probe sensing area, necessary to operate the vorticity probes, is valid only if the probe has sufficient spatial resolution. In order to study the geometrical arrangements presented in the previous paragraph, the spatial resolution of $S_y^+ = S_z^+ = 4$, $\Delta^+ = 1$ was taken for all array configurations shown in Fig.8. The best spatial resolution achieved so far was close to these values in *y*-direction, but the most of the probes used in various experiments have much worse spatial resolution. In order to analyze haw does the spatial resolution affects the measurements accuracy it is necessary to vary the array separation with proportional varying of the arrays size or keeping the array size unchangeable. This should be done for each of the configuration shown in Fig.8. Having in mind that the VW3 arrangements has superior array configuration, Vukoslavčević et al (2009) analyzed the influence of the spatial resolution for this configuration. They varied proportionally the dimension of this configuration shown in Fig.10 on a DNS mesh of Piomelli et al. (2000) channel flow , taking the S_v^+ and S_z^+ values as 2, 4, 8 and 12.

This choice is based on the spatial resolution achieved in the several experiment; Vukoslavčević et al. (1991), Balint et al. (1991), Wallace et al. (1992), Ong and Wallace (1995), Ong and Wallace (1998), Loucks (1998). In all of these experiments the spatial resolutio was close to $S^+ = S_y^+ \approx S_z^+ \approx 8$, what coresponds to array separation in *z* direction of about 1.3 mm. So the consequence of the better or worse spatial esolution of the one achieved so far should be clear. The effect of spatial resolution on the ω_z vorticity rms values is presented in Fig.11.

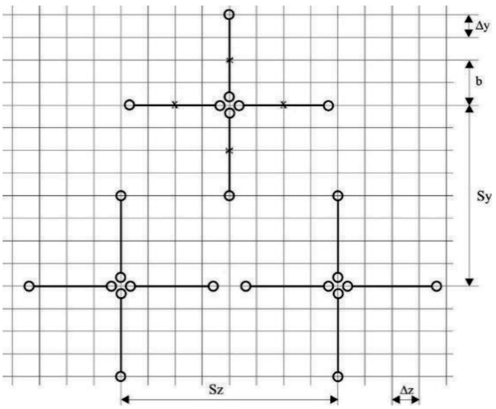


Fig. 10 Sketch of 12-sensor probe represented as points on a DNS mesh with $S_y^+ = S_z^+ = 8$ and $\Delta y^+ = \Delta z^+ = 1$

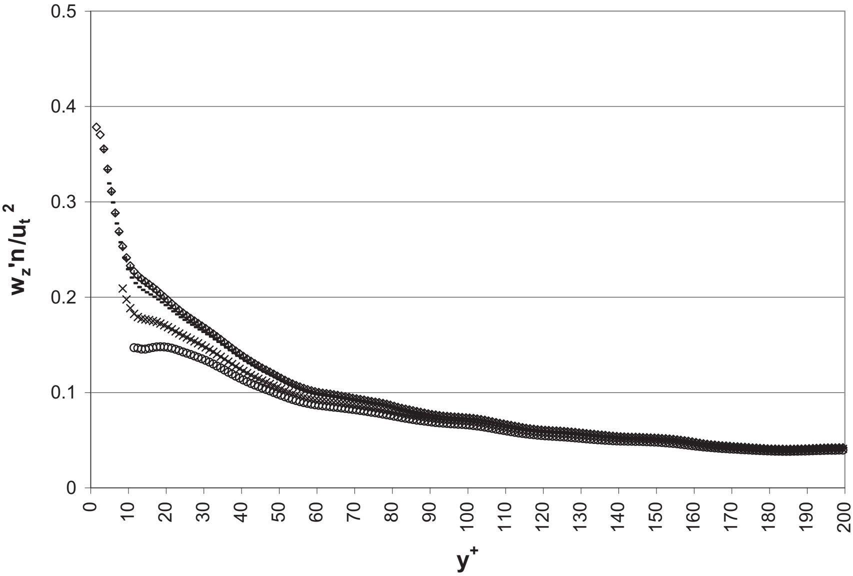


Fig.11 Attenuation of the ω_z rms for different array separations of 12-sensor probe plus configuration; DNS (◊), S_v^+ =2 (+), S_v^+ =4 (-), S_v^+ =8 (x), S_v^+ =12(o)

There is almost no resolution effects for the S+ = 2 and 4 cases. For S+ = 8, ω_z is attenuated about 18% at $y^+ = 15$, and the simulation with experimental probe coefficients is identical to that with the ideal probe coefficients for this array separation. The attenuation with the S^+ = 12 separation is considerably larger, reaching about 30% at $y^+ = 15$. Similar results are obtained for ω_x and ω_y vorticity components. It is clear that to eliminate the spatial resolution problem, a probe of $S^+ = 4$ or half the size of the smallest existing probes has to be constructed. Although it looks possible from the technical point of view by reducing the sensor diameters from 2.5 to 1.2 microns, serious problems related to the thermal contamination and flow blockade by the prongs are expected.

The influence of the spatial resolution is extremely strong on the accuracy of the measurements of the streamwise velocity gradients. As it was mentioned in Section 5, the most of the vorticity probes are not capable of measuring the streamwise velocity gradients. These gradients are usually estimated using Taylor's hypothesis (1938), exp. (5.3). The only vorticity probe that is, in principle, capable of streamwise velocity gradients measurements is **TKD5** model designed by Galanty et al. (2003), Fig.8(e). This probe has a central array moved upstream to measure the velocity components at a point separated by a distance Δx from the plane of the other four arrays. In order to make the space for this array and reduce the thermal contamination created by the central array to the other arrays, the dimension of this type of probe has to be higher than the dimension of the other models. The model used by Galanty et al. (2003) and Gulitski et al. (2007) was double the size of the **VW3** model. A minimal dimension of this type of probe can be obtained by replacing the 2.5 micron sensors with 1.2 microns sensor. In that case the dimension of this probe will be $S_y^+ = S_z^+ = 8$ and S_x^+ =4. Still the problem of the thermal contamination and sensor sensitivity is open, so this is a rather optimistic expectation to be realized in the near future. The results of the analysis of the accuracy of the streamwise velocity gradients measurements is presented in Fig.12, Vukoslavčević and Wallace (2013).

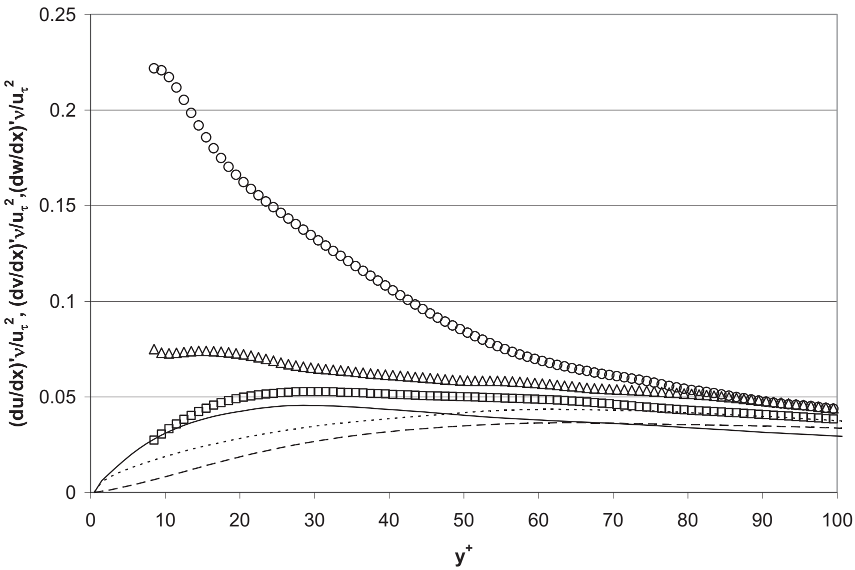


Fig.12 Comparison of the DNS and simulated rms distributions of the streamwise velocity gradients of the TKD5 array configuration with the central array moved upstream. DNS: *solid line,* $\partial u / \partial x$; *dash line,* $\partial v / \partial x$; *dotted line,* $\partial w / \partial x$. TKD5: *circle,* $\partial u / \partial x$; *square,* $\partial v / \partial x$; *triangle,* $\partial w / \partial x$, with $S_x^+ = 4$ and $S_y^+ = S_z^+ = 8$.

In the near the wall region, the error is over 100%, being the worst for the $\partial u / \partial x$ velocity gradient. Not only that the measurement of the streamwise velocity gradients by such a configuration is not reliable, but also it is hard to imagine any multi-sensor hot-wire probe configuration that can simultaneously measure all three velocity gradients in the x-direction with sufficient accuracy.

As mentioned above, in order to study the probe spatial resolution all probe dimensions (prong separation, array size and array separation) are varied proportionally. By reducing the array size the error in velocity measurements will be reduced (the assumption of linear velocity variation over the array will be more accurate) which will increase the accuracy of velocity gradient measurements. On the other hand, reducing the array separation results in increasing of the error in the velocity gradient measurements (the same error in velocity measurements is divided by smaller separation between the arrays). Therefore, it is not clear in advance whether the error in velocity gradient measurements will decrease or increase by proportional decreasing the probe dimensions. In order to study this effect Vukoslavčević and Wallace (2017) analyzed the $\partial v / \partial y$ gradient, using the DNS of Piomelly et al. (2000). The influence of four different ratios of array to array separation size are presented in Fig.13.

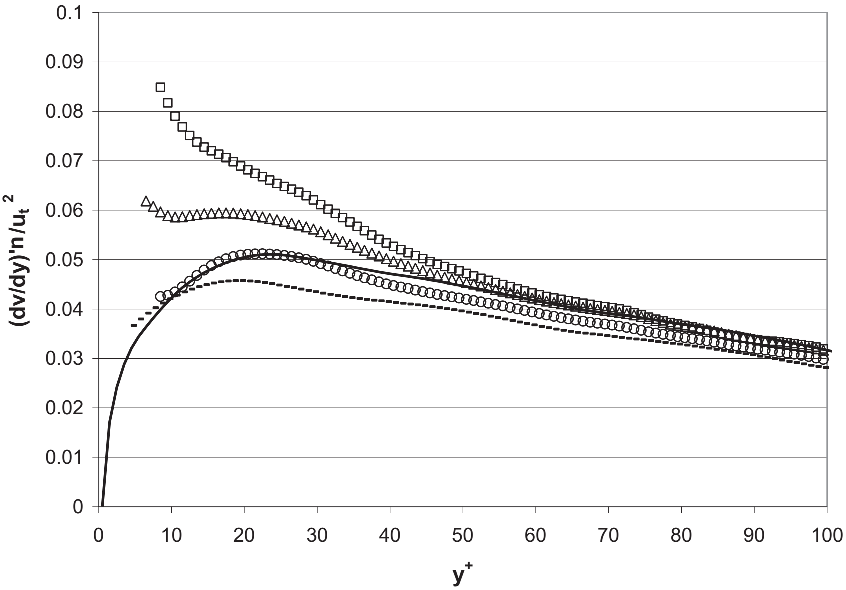


Fig.13 Effects of the various ratios of array to array separation size for the **VW3** array: *Solid line* DNS, *square* $S_y^+ = S_z^+$=9 and b^+=*2*, triangle $S_y^+ = S_z^+$=4.5 and b^+=1, *circle* $S_y^+ = S_z^+$ =9 and b^+=1, *dash* $S_y^+ = S_z^+$=9 and b^+=0 (perfect array)

In a case of $S_y^+ = S_z^+$=9 and b^+=*2*, the measurement error is about 25% at y^+=20, as it can be seen from Fig.13. By reducing all dimensions in half ($S_y^+ = S_z^+$=4.5 and b^+=1), the error is decreased to 16%. However, keeping the array separation unchanged and reducing the array size only ($S_y^+ = S_z^+$=9 and b^+=1), the measurement error is practically zero. It is clear that in case of $\partial v / \partial y$ measurement it is better to reduce the array dimension only rather than reducing all probe dimensions proportionally. An optimal ratio of array dimension to the array separation distance obviously exist. Vukoslavčević and Wallace (2013a) studied a simultaneous influence of the array size, configurations and separation on the measurements accuracy. They have shown that the velocity gradients and, therefore, the vorticity components are affected differently, what makes the optimization process very complex.

7.3 The influence of the technical aspects

The sensor temperature defined by the overheat ratio is one of the most important parameter to be optimized. The higher overheat ratio is the higher sensor sensitivity and signal to electronic noise are. Unfortunately, the high overheat ratio cause a thermal contamination of the sensors. In other word, the heat coming from a neighbor sensor reduce the sensor output what underestimate the value of measured velocity. The problem was noticed by Vokoslavčević et al. (1991). They had to keep the overheat ratio small enough to avoid the thermal contamination within and between arraays. The other parameters to optimized is prongs diameter. The ticker the prongs are the higher is the flow distortion or aerdinamical blockade. The thin prongs increse the prongs resistance what afect the sensor frequence response and signal stability. To increase the ferquence response and avoid the signal instability, besides the probe parameters, it is necessary to simultaneously optimize several electronic circuit components like: resistors, amplifiers, capacitors and transistor. In additional to the complex theoreticcal analysis, this optimisation requires sophisticated labratory experiments. The probe fabrication and calibration method is also a complex proces, Vukoslavčević and Wallace (2007). To make the probe available to the brother oudience all of these proces has to be improved and optimized.

8. CONCLUSIONS

In order to measure all three vorticity components it is necessary to simultaneously measure the cross-stream and streamwise velocity gradients. The hot-wire vorticity probes developed over last forty years are capable of measuring the velocity gradients in cross-stream plane with reasonable accuracy. There was only one attempt to develop a probe to be able to simultaneously measure both; cross-stream and streamwise velocity gradients. An analysis of measurement accuracy, based on the DNS data bases, have shown that due to the pour spatial resolution the streamwise velocity gradients can be in error over 100%. So, the only way to determine these gradients, so far, is by using the Taylor's hypothesis of frozen turbulence.

Various probe models with specific geometrical arrangements of the array and sensors and their dimensions have been developed and used in a series of measurements in laboratory conditions as well as in atmospheric turbulence. Using the DNS databases an analysis of the influence of the probe geometrical arrangements and dimensions on the measurements accuracy has been performed. A minimum of 8 viscous length between arrays centers is necessary to achieve a reasonable measurements accuracy of the vorticity components. This means that even for a laboratory conditions measurements it is necessary to place 12 sensors and 24 prongs in a circle of less then 2.5 mm in diameter. To increase the measurements accuracy and make the vorticity probes useful in various technical conditions with high turbulence level flows it is still necessary to overcome serious technical difficulties.

The further efforts should be aimed at replacing the sensor of 2.5 microns with 1.2 microns, optimizing the overheat ratio and improving the electronics components of the anemometers boards to reach the higher frequency response and signal stability. Various DNS databases can be used to further optimize the probe geometry and dimensions. Further optimization of the overheat ratio, reducing the thermal contamination and improving the frequency response and probe fabrication method requires sophisticated laboratory conditions. A general approach to optimize the measurement accuracy of velocity and therefore the vorticity components has not been found yet. Optimization depends on many parameters; the array configuration, the sensor configuration and the technical possibilities to construct a probe of a given dimensions.

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