Using DNS to compare the performance of virtual hot-wire probe sensor and array configurations for simultaneous measurement of the velocity vector and velocity gradient tensor

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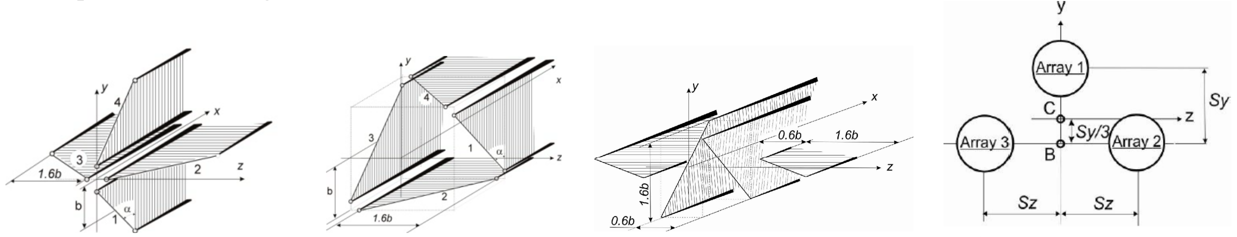
Abstract: A highly resolved DNS of a minimal channel flow is used to compare, virtually, the performance of multi-sensor probes used to simultaneously measure the velocity vector and the velocity gradient tensor. Statistics obtained with configurations of sensors in arrays that have been used in previous experimental studies are compared to those obtained with a new configuration designed to optimize performance.

For over twenty-five years multi-sensor, hot-wire probes of various configurations have been used to simultaneously measure the velocity vector and the velocity gradient tensor in turbulent flows. The first successful measurements were presented by Balint et al.[1] at the very first European Turbulence conference, also held in Lyon. Such measurements had long been a primary goal of experimentalists (see Laufer[2] and Willmarth[3]) in their attempt to understand the structure of and transport process within turbulent flows. During this same period direct numerical simulations (DNS) emerged as a powerful method to investigate these flows. Moin and Spalart[4] were the first to use DNS to virtually examine the performance of a two-sensor X-array probe with the sensors idealized as points in the numerical grid. Subsequently, Suzuki and Kasagi[5] and Pompeo and Thomann[6] also used DNS for similar studies. In a series of recent papers[7,8,9,10,11] Vukoslavčević, and coworkers have used a highly resolved minimal channel flow DNS (see Jiménez and Moin[12]) to examine, virtually, the spatial resolution and sensor and array configuration effects on the accuracy with which turbulent bounded flow statistics, including those based on both the velocity vector and the velocity gradient tensor, can be measured with multi-sensor hot-wire probes.

The Reynolds number of the minimal channel flow is $Re_\tau = 200$. The equations of motion were solved using a fractional step method, where both the advective and diffusive terms were treated explicitly using an Adams-Bashforth scheme. All spatial derivatives were discretized with second-order, central finite differences on a staggered grid. The size of the computational domain was set to 2h x 2h x h, where h is the channel half width, and it was discretized using 400 x 400 x 200 grid nodes in the streamwise, wall normal and spanwise directions, respectively. The grid was uniform in all directions, and the resulting resolution is $\Delta x^+ = \Delta y^+ = \Delta z^+ \sim 1$, where "+" denotes normalization with the viscous length. This permits the existence of about two low and high speed streaks. Near the wall the grid size is a little less than 2/3 of the Kolmogorov length in each coordinate direction and a little more than 1/4 of this length at the channel centerline. To be able to obtain reasonably adequate statistical convergence for the virtual probe investigations, a database of approximately 50 independent instantaneous realizations over 15 eddy turnover times was generated. The mean and rms velocity distributions from this minimal channel flow simulation compare very well to those from the full channel flow DNS of Kim et al.[13] at a similar Reynolds number.

In this paper we use this same minimal channel flow DNS to compare the performance of two different configurations of the sensors within an array that have been used in the past by us and others, to that of a new configuration designed to optimize performance. The configurations that are compared are the "Plus" (PL), "Square" (SQ) and the new, optimized "X-Parallel" (XP) one shown in Fig. 1(a-c). All of these arrays are arranged in the same 3-array configuration shown in Fig. 1(d), and they all are spaced so that $Sy^+ = 6$ and $Sz^+ = 3.4$. For all but the XP configuration, this separation of the arrays is the minimum that is practical to fabricate. However, for the XP configuration it is possible to make the separation Sy^+ as small as 3.4. For this new sensor configuration, we also will vary $Sy^+ = Sz^+$ from the smallest size of 3.4 up through values of 4, 6 and 7.5 in order to see the effects of spatial resolution on the statistics from a probe of this design.



(a) (b) (c) (d)

Figure 1. Configurations of sensors with arrays of multi-sensor probes used to simultaneously measure the velocity vector and the velocity gradient tensor: (a) "Plus" (PL), (b) "Square" (SQ), (c) "X-Parallel" (XP). (d) Arrangement of a three-array multi-sensor probe.

In Fig. 2(a), as an example of the statistical results, the distribution of the rms spanwise vorticity component is shown for the three array configurations of three-array probes as well as for an "ideal" three-array probe where the velocity components at the centers of each array are the DNS values. This latter case removes the effects of the finite size and sensor configuration of each array on the statistics so that only the resolution effects of the separation distances between the arrays can be separately observed. For these fixed array separations of $Sy^+ = 6$ and $Sz^+ = 3.4$, the XP configuration yields values that are nearly identical to those for the "ideal" probe and that are clearly somewhat better resolved than those from the PL and SQ array configurations. Fig. 2 (b) shows the effect of spatial resolution on the spanwise vorticity component distribution when the separation distances between the arrays are increased from the minimum values that are practical to fabricate. For $Sy^+ = Sz^+ = 3.4$, the virtually "measured" values are only a little attenuated, but this attenuation becomes quite large for $Sy^+ = Sz^+ = 7.5$.

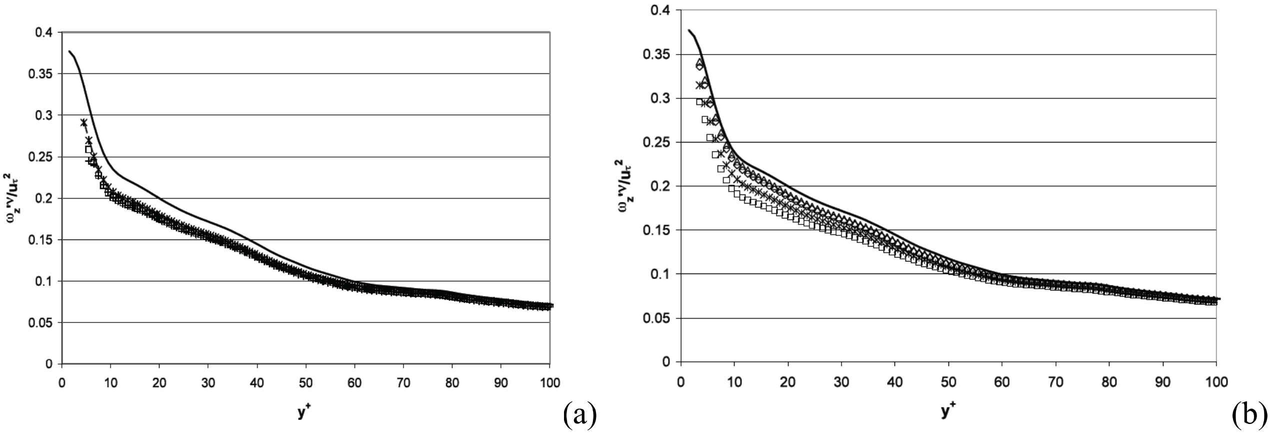


Figure 2. (a) Distributions of the rms values of the spanwise vorticity component for: (a) the PL (plus), SQ (square), XP (star) and "ideal" (dashed line) configurations of a three-array probe with array separations of $Sy^+ = 6$ and $Sz^+ = 3.4$; (b) the XP array configuration of a three-array probe with array separations of $Sy^+ = Sz^+ = 3.4$ (triangle), 4 (diamond), 6 (star) and 7.5 (square). Both sets of data in (a) and (b) are compared to the DNS (solid lines).

Full sets of statistics of turbulence properties derived from the velocity vector, the velocity gradient tensor (rms, Reynolds shear stress, skewness factor distributions, turbulence production and dissipation rates and velocity-vorticity component correlations) will be presented to observe what sensor and array configurations and their spatial separations yield the best results.

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