Laboratory study of noise in turbulence measurements using acoustic Doppler velocimetry

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Background

- Acoustic Doppler velocimeters (ADVs) were mainly developed as a field tool.

- Laboratory measurements allow benchmarking of the ADV.

Background

<u>ADV advantages:</u>

- Three-dimensional velocity measurements
- The ability to measure in non-clean environments
- Minimal interference of the probe with the flow
- Relative robustness
- Portability

<u>ADV disadvantages:</u>

- Its ability to accurately measure turbulence statistics
- Inaccuracy in near-bed measurements
- Relatively large sampling volume

Motivation

- The results of experiments in our laboratory benchmarking an ADV in an axisymmetric turbulent jet showed that the RMS velocities were overestimated by the ADV.
- We attempt to explore the sources of noise and improve the precision of measured turbulence statistics.

Literature review

The ADV predicts the mean velocity relatively accurately. However, its precision in making turbulence measurements has been questioned (Voulgaris and Trowbridge, 1998).

Sources of error:

- Sampling error related to the accuracy of the ADV's A/D conversion.
- Doppler noise (inherent to the technique), which is flow-related and due to (1) turbulence and particle scattering, (2) beam divergence, and (3) the finite residence time of the particles in the sampling volume.
- Mean velocity gradients in the sampling volume.
- A relatively large sampling volume, which can limit ADV's accuracy, especially in turbulence measurements.

Literature review

- The most significant source of error in turbulence measurements by acoustic Doppler velocimetry is Doppler noise (Lohrmann *et al*., 1994).

- Hurther and Lemmin (2001) characterized the Doppler noise as:

    - i) having a flat spectrum over the frequency domain.
    - ii) being unbiased ($<\sigma_i> = 0$), therefore not affecting the mean velocity.
    - iii) being statistically independent of the true velocity fluctuations and true Doppler frequency.
    - iv) having statistically independent noise from one receiver to the next ($<\sigma_i \sigma_j> = 0$, $i \neq j$).

Literature review

Suggested methods for reducing noise:

- De-spiking filters, including those of Goring and Nikora (2002) and Cea *et al*. (2007).
- Nikora and Goring (1998) subtracted the measured noise in still water from the measured RMS velocity to estimate the true velocity. However, Lemmin and Lhermitte (1999) remarked that the Doppler noise is a function of the flow's mean velocity.
- In the noise reduction method of Hurther and Lemmin (2001, 2008), the noise can be calculated from two vertical velocities and removed from the horizontal velocities.

Experimental facilities

- Experiments were carried out in a 2.4m x 1.5m x 0.9m section of a water tank.

Tank: 6 m x 1.5 m x 1 m

ADV parameters

- The velocity field was measured by a Nortek Vectrino 10 MHz ADV.
- The sampling rate was 25 Hz (the maximum).
- The sampling volume of the ADV was set to its largest (0.26 cm^3).
- Neutrally buoyant particles were added to the filtered water to increase the signal-to-noise ratio of the ADV.

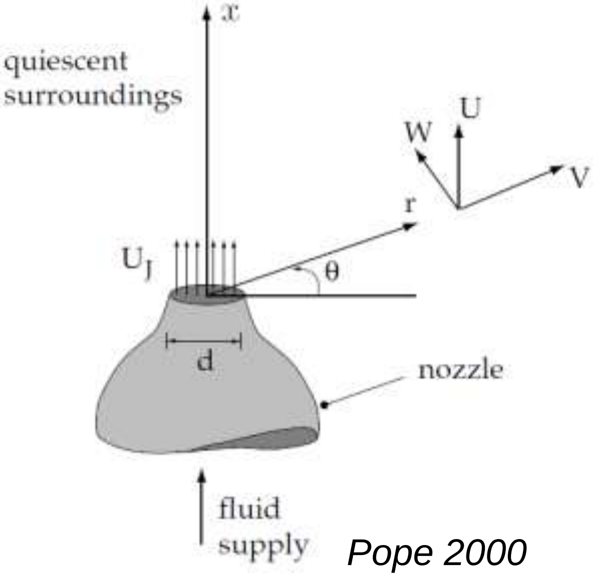
Nortek Vectrino ADV

Nortek.com

1st objective

- To study the ability of the ADV to measure turbulence statistics.

- To benchmark the ADV's performance in measuring turbulence statistics in an axisymmetric turbulent jet.

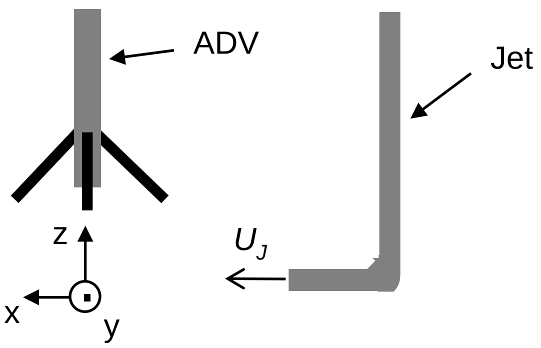


Pope 2000

Experimental setup: jet and ADV

An axisymmetric turbulent jet issued in the water tank:

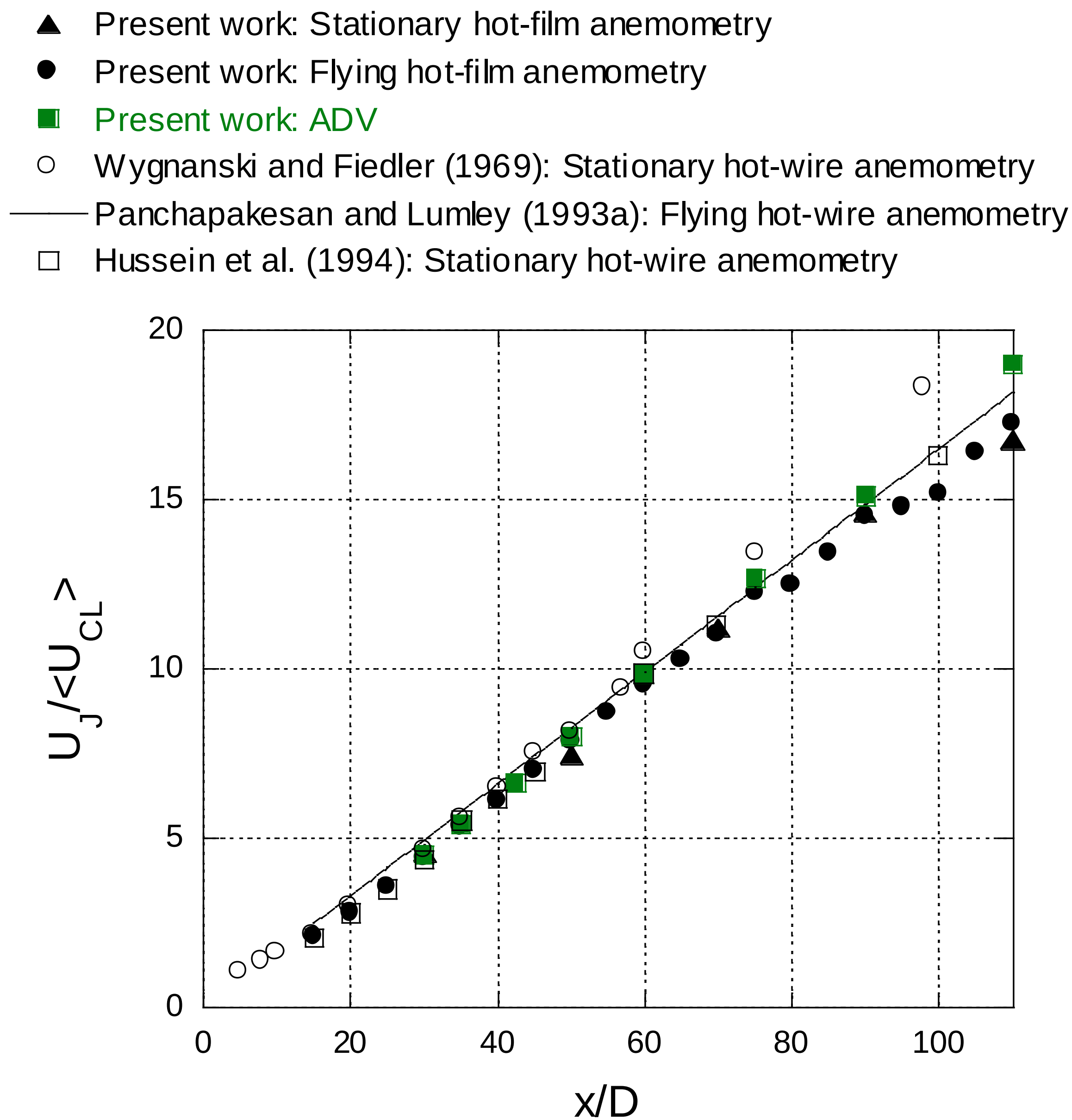
- $Re = U_J D/\nu = 10{,}600$ (D = 8 mm)
- Measurements within self-similar region ($30 \leq x/D \leq 110$)
- Jet axial velocity (u) is measured along the x-direction of the probe. Jet radial velocities (v and w), are measured along the y- and z-direction of the probe.



Benchmarking

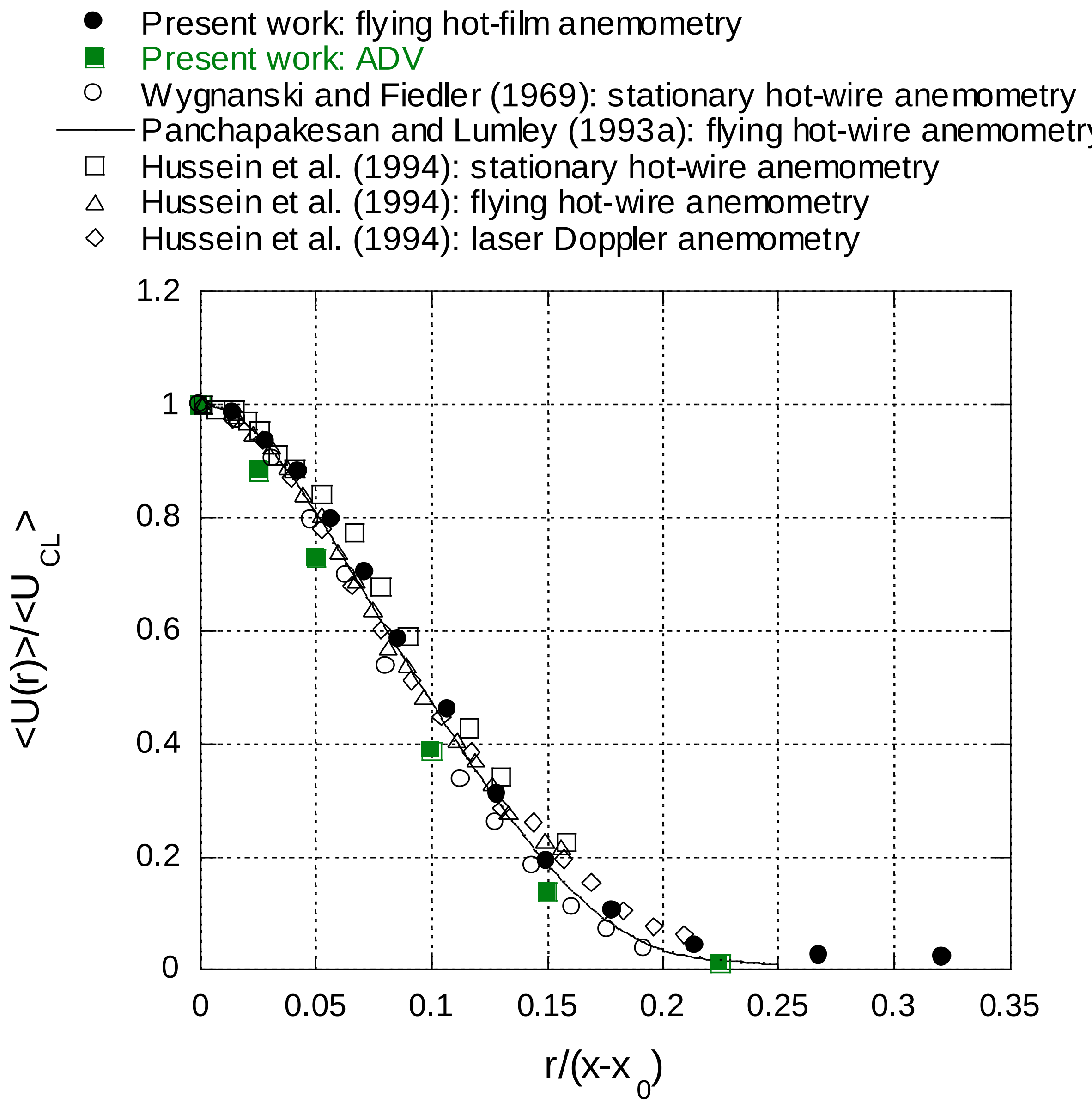
- Benchmarking the ADV along the axis of a turbulent jet.

- Downstream evolution of the centerline axial mean velocity of an axisymmetric turbulent jet at Re = 10,600



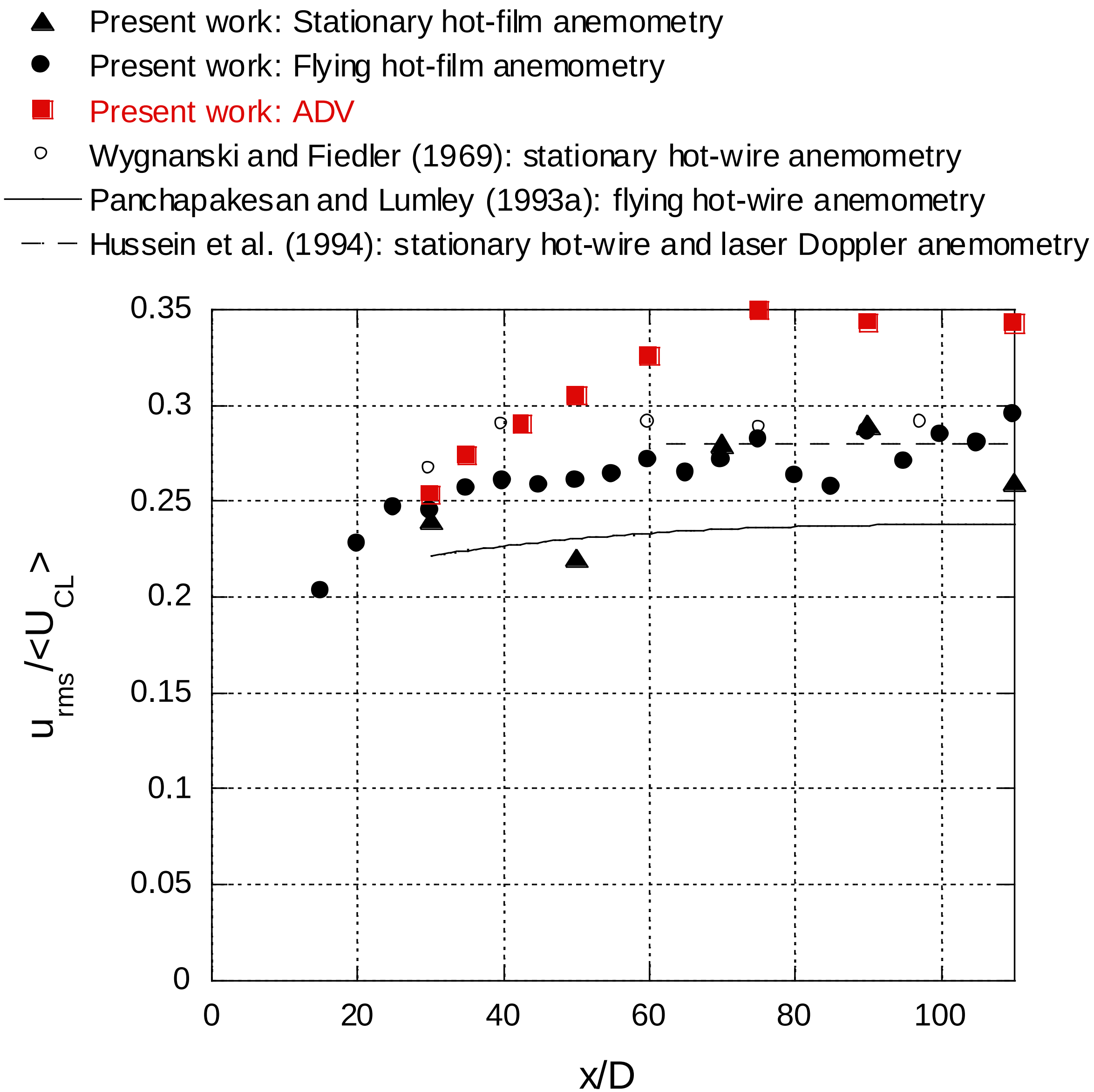
Benchmarking

- Mean axial velocity profile of an axisymmetric turbulent jet for Re = 10,600. $x/D = 35$, $x_0 = 0$.
- Therefore, ADV measures the mean velocity accurately.



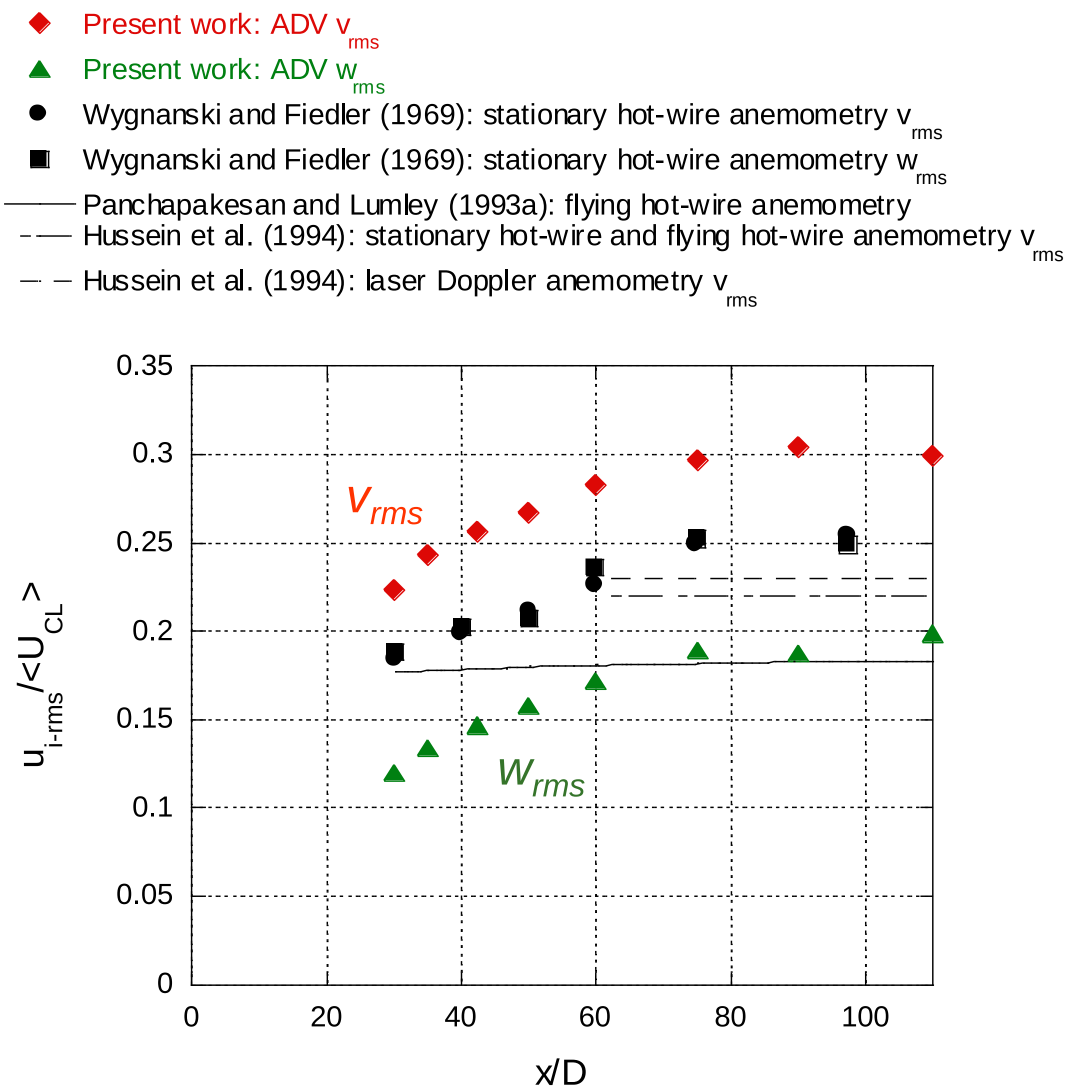
Benchmarking

- Downstream evolution of u_{rms} at the centerline of the jet.
- u_{rms} along the centerline is overpredicted.



Benchmarking

- Downstream evolution of the radial RMS velocity at the centerline of the jet.
- By symmetry, v_{rms} and w_{rms} should be the same.
- w_{rms} agrees well but v_{rms} is overestimated.



2^{nd} objective

- To improve the turbulence statistics measured by the ADV.
  - Test post-processing filters.
  - Find a relationship between the Doppler noise and the mean velocity of the flow is needed to subtract the noise from the RMS velocities.
  - Test noise reduction methods.

Post-processing filters applied to the data

- Post-processing filters tested on the present turbulent jet data:

  i) Nikora and Goring (1998)
  ii) WinADV (Goring and Nikora (2002) phase-space thresholding method modified by Wahl (2002))
  iii) Cea *et al*. (2007)

  However, they did not reduce the RMS velocities significantly as the signal quality was high in the present laboratory flow.

- Lemmin and Lhermitte (1999) remarked that the Doppler noise is a function of the mean velocity of the flow. They questioned the filter of Nikora and Goring (1998) in which velocity measurements in a quiescent background were used to predict the Doppler noise.

Doppler noise and the mean velocity

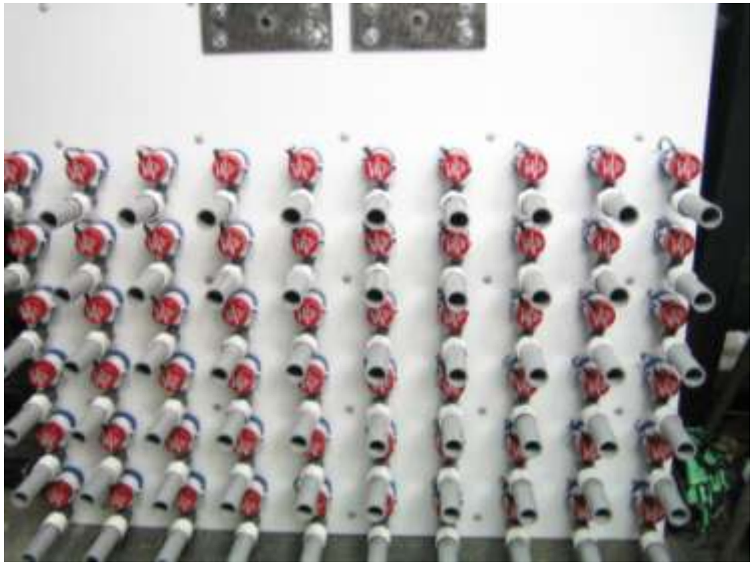
To investigate the relation between Doppler noise and the mean velocity, and to estimate its effect on turbulence statistics, velocity measurements were made in a:

i. Quiescent background
ii. Quiescent background with the ADV moving at a constant speed using a traversing mechanism
iii. Homogeneous isotropic turbulence with no mean flow
iv. Homogeneous isotropic turbulence with an artificially generated mean velocity by moving the ADV at a constant speed using a traversing mechanism.

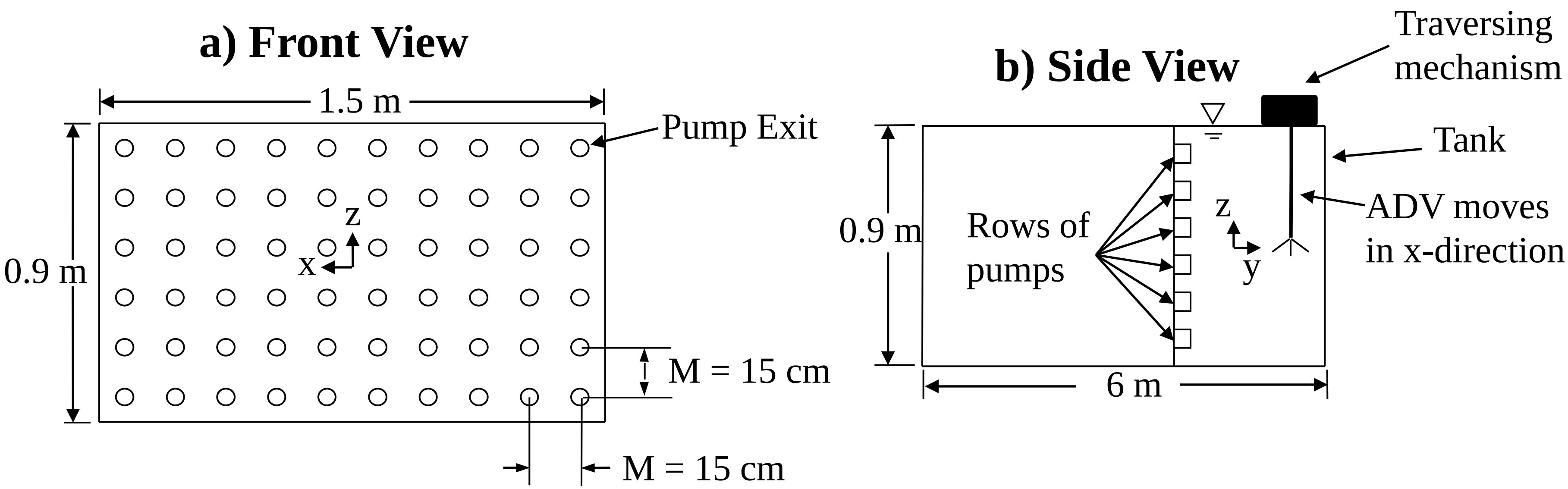
Experimental facilities

- A random jet array (Variano *et al.* 2004, 2008) located within this section was used to generate a turbulent background with zero mean velocity.
- A traversing mechanism was mounted on top of the tank for moving the ADV at different constant speeds.

random jet array

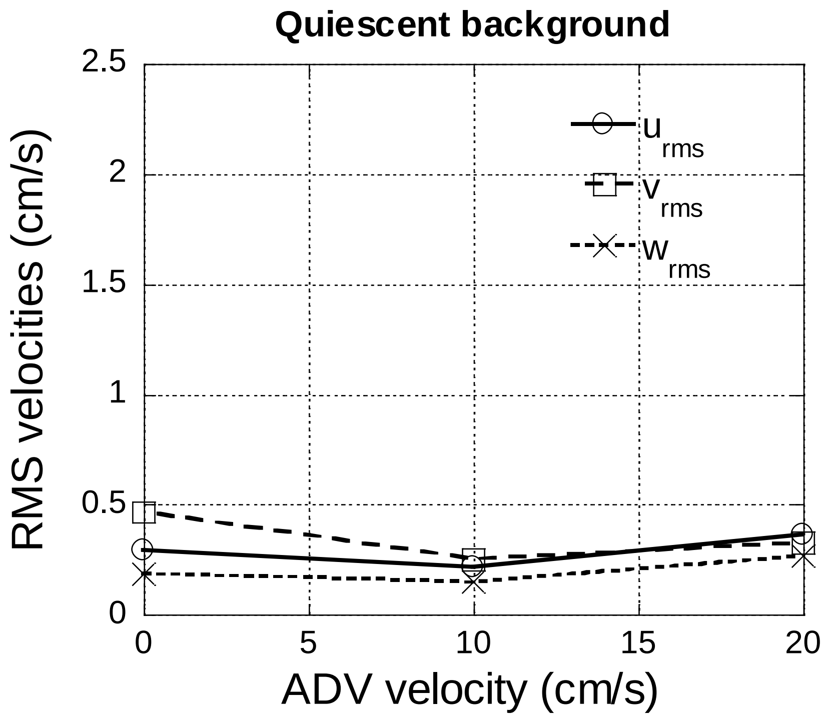


Experimental setup: random jet array and ADV in the tank



Results: Quiescent background

- The measured RMS velocities are attributable to both noise and experimental error.
- No clear relationship can be detected between the noise and the mean velocity.

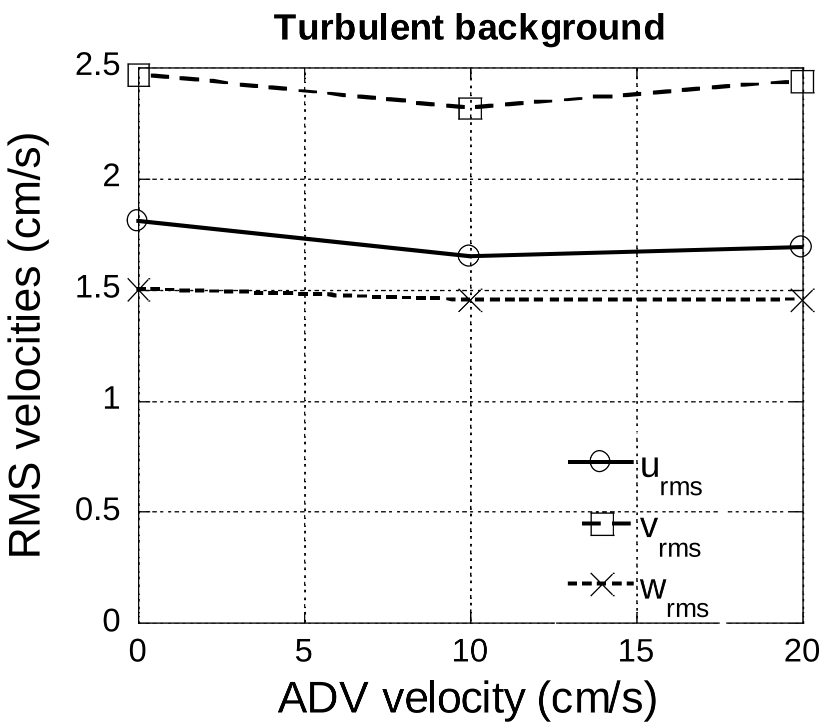


- Subtracting the RMS velocities measured with the ADV moving at a constant speed in quiescent background from the measured jet RMS velocities, reduced the jet RMS by less than 1%.

Results: Zero mean flow turbulence

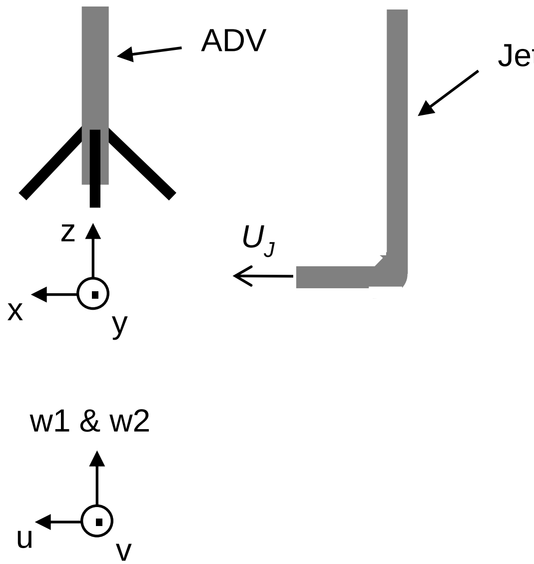
- No clear relation can be observed between the RMS velocities and the mean flow.

- In other words, the measured RMS velocities in a turbulent flow with no-mean velocity do not significantly differ from those measured in the same flow when imposing a constant mean velocity by translating the ADV.



Hurther and Lemmin (2001) noise reduction method

- Because the noise signals of the two vertical velocities are uncorrelated, the covariance is noise free. Therefore,
  $\langle w_1 w_2 \rangle_{Measured} = \langle w_1^2 \rangle_{True} = \langle w_2^2 \rangle_{True}$.
- Assuming the correlation between the velocity and the noise to be zero, variance of the noise, $\langle \sigma_w^2 \rangle$, can be found from:
  $\langle w^2 \rangle_{Measured} - \langle w_1 w_2 \rangle_{Measured} = \langle \sigma_w^2 \rangle$.
- Using the transformation matrix, the variances of the noise can then be calculated for the u and v velocity components. Subsequently, the variance of the noise can be subtracted from the variances of the u and v velocities.



A proposed alternate noise reduction method

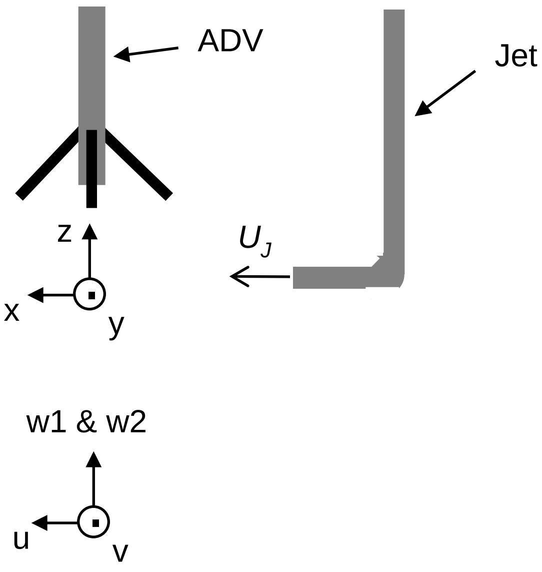
- For the axisymmetric jet: $\langle v^2 \rangle_{True} = \langle w^2 \rangle_{True}$ due to symmetry.

- Assuming the noise in $\langle w^2 \rangle$ to be negligible, then:

$$\langle v^2 \rangle_{Measured} - \langle w^2 \rangle_{Measured} = \langle \sigma_v^2 \rangle.$$

- $\langle \sigma_v^2 \rangle$ can be converted to $\langle \sigma_u^2 \rangle$ using the transformation matrix.

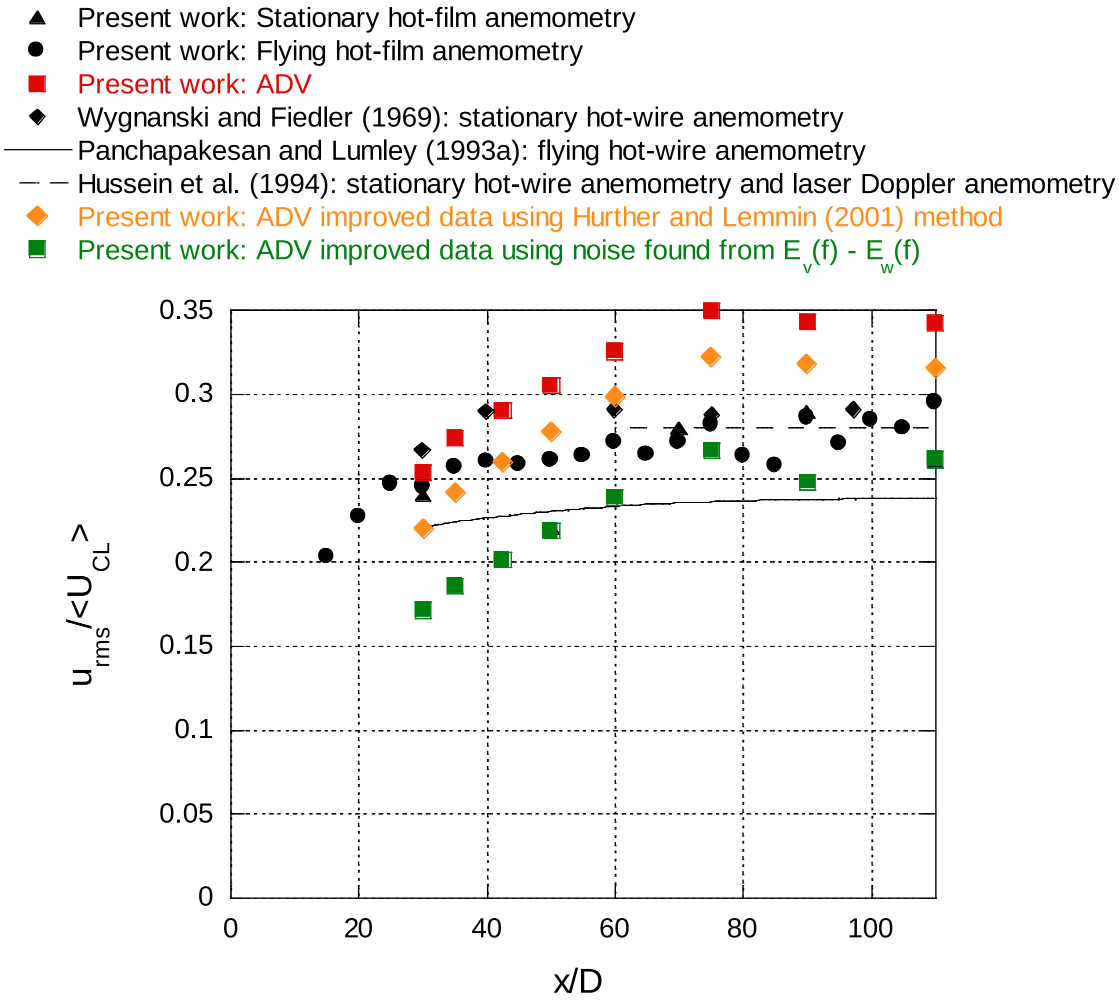
- Assuming the correlation between the velocity and the noise to be zero, the variance of the noise, $\langle \sigma_u^2 \rangle$, can be subtracted from the variances of the u velocity.



Results

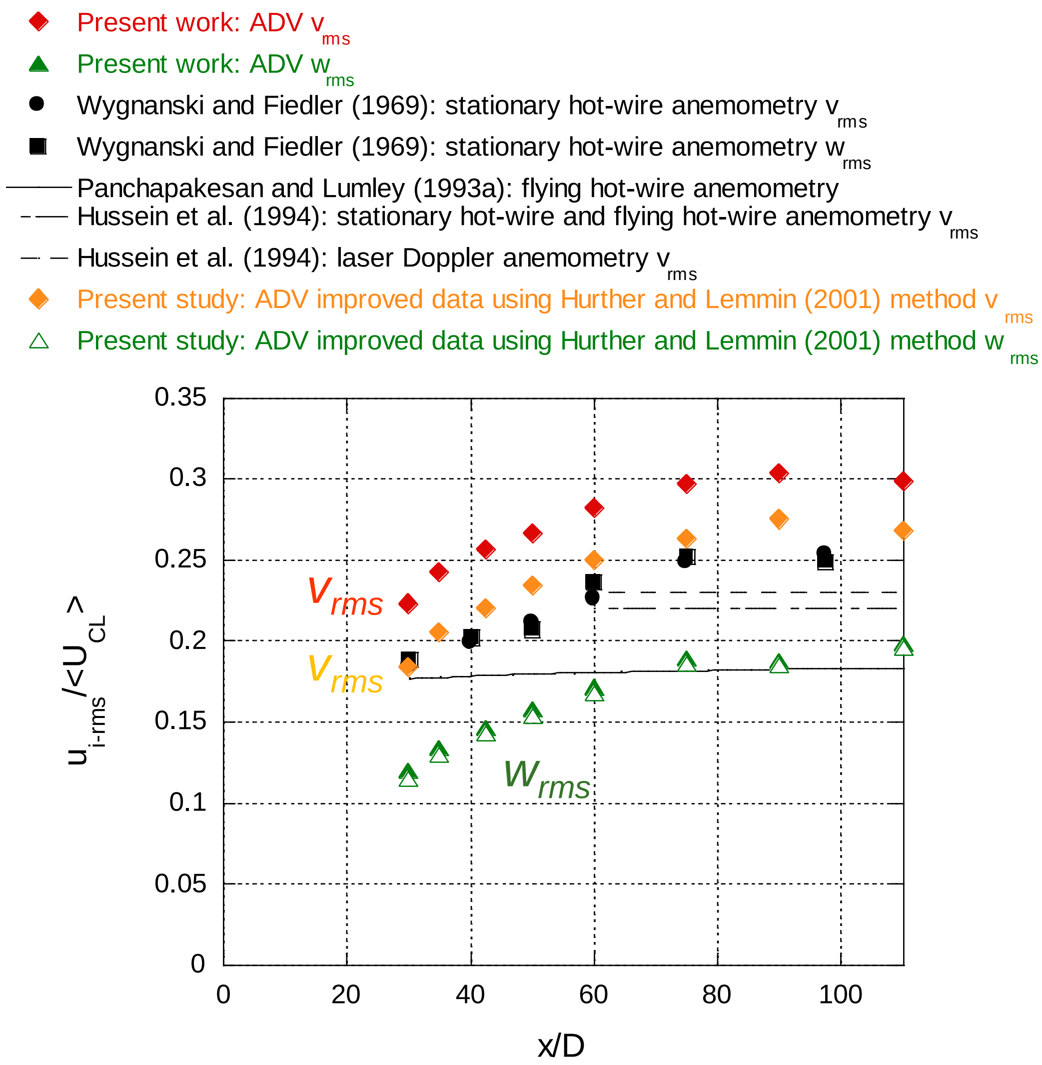
- Although the u_{RMS} velocities measured by the ADV were improved using the noise reduction method of Hurther and Lemmin (2001, 2008), they were still higher than the accepted values.

- Our method reduced the RMS velocity to accepted values measured by other instruments.



Results

- The noise reduction method of Hurther and Lemmin (2001, 2008), reduces v_{rms} which is still higher that the accepted values.
- w_{rms} does not change significantly.



Conclusions

- ADV overestimates u_{RMS} and v_{RMS} measured along the horizontal axes of the ADV probe (x and y) in an axisymmetric turbulent jet. However, w_{rms} measured along the vertical axis (z) was accurately predicted.

- In contrast with the argument of Lemmin and Lhermitte (1999), the Doppler noise is not a function of the mean flow velocity for the range of velocities studied herein.

Conclusions

- Although u_{RMS} and v_{RMS} were improved using the noise reduction method of Hurther and Lemmin (2001), they were still higher than the accepted values.
- We proposed a method that reduced u_{RMS} down to the accepted values.
- This method can be used to find the true RMS velocities: i) in axisymmetric flows, and ii) in any flow, if two measurements in two different probe orientations are made.

The end