



Norwegian University of  
Science and Technology

# Measurement methods in turbulent flows

**Neda Draskovic**

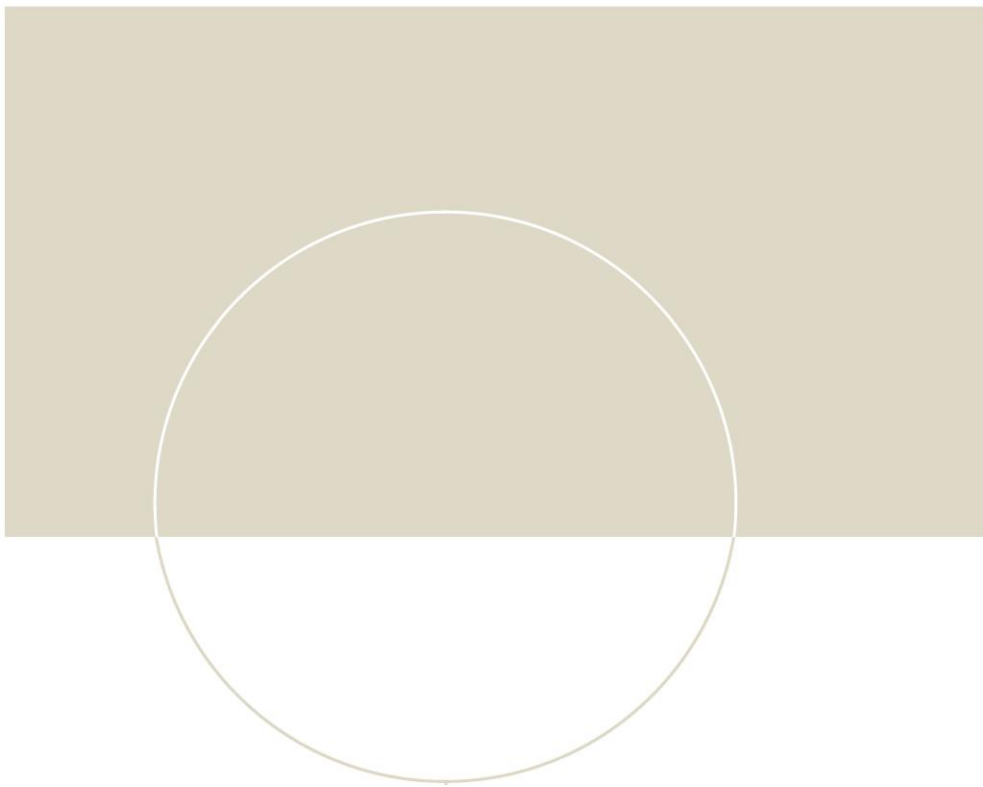
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Supervisor: Lars Sætran, EPT

Norwegian University of Science and Technology  
Department of Energy and Process Engineering





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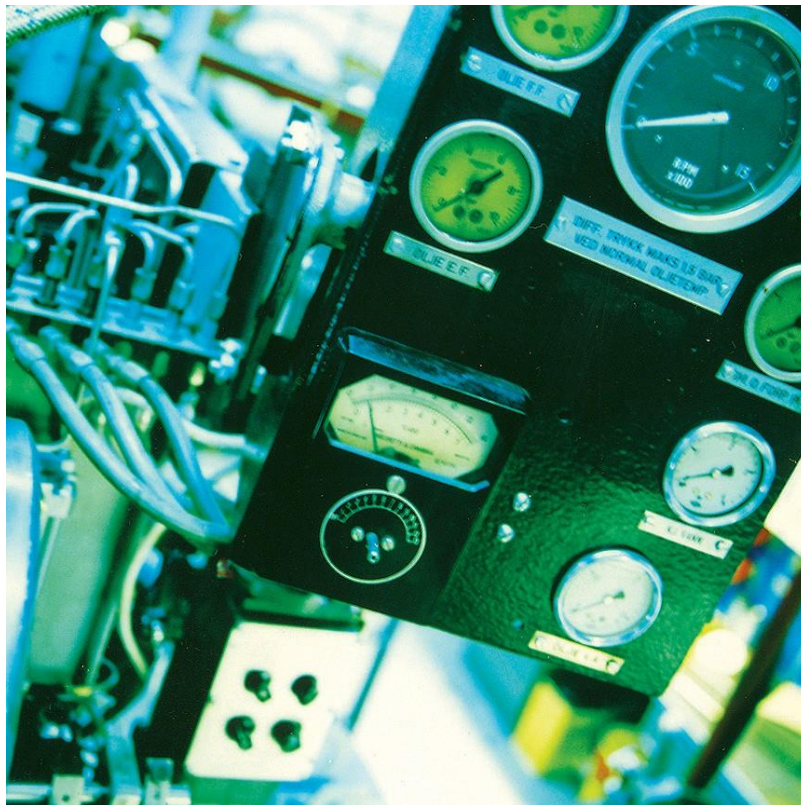
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Science and Technology  
Faculty of Mechanical  
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Master's thesis

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## Abstract

In this Master Thesis, the performance of a cobra probe in turbulent flows is investigated. For this purpose, cobra probe was used in two experiments that were done in the Fluid Mechanics building at NTNU. First experiment was done for the fully developed pipe flow to test out cobra probe and estimate the errors. Measuring instruments cobra probe and pitot probe were used in this experiment. The obtained results for the mean flow velocity were compared. Also, results of turbulence intensity and Reynolds stress from the previous studies were used as a reference in cobra's probe performance analyses. This experiment was used as an initial test for better comprehension of a cobra probe's performance in complex flows with increased free stream turbulence levels. The main goal was to test out cobra probe for such flows, so that the second experiment took place in the recirculating wind tunnel with a grid placed at the entrance of its test section. The measurements were done simultaneously by cobra probe and LDV that were set 12 diameters downstream the wind turbine model. The discrepancy between the results of measurements that these two measuring instruments had provided were studied in this thesis. The cobra probe showed to be able to measure with quantified errors which are within the values for the measurement uncertainty of  $\pm 0.5 \frac{m}{s}$  that is set in the manufacturer's specifications.





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## Nomenclature

Symbol	Definition
$u$	Instantaneous velocity component
$\bar{u}$	Time averaged velocity component
$V$	$V=Q/A$ -average velocity in a pipe flow
$\mu$	Dynamic viscosity
$\nu$	Kinematic viscosity
$d$	Pipe diameter
$D$	Wind turbine diameter
$Re_d$	Pipe Reynolds number
$u'$	Fluctuating part of instantaneous velocity
$\tau_w$	Wall shear stress
$\delta$	Thickness of wall layer in a pipe flow
$\rho$	Fluid density
$k$	Constant
$B$	Constant
$dA$	Differential area
$U_M$	Mean wind speed
$I_{uu}$	Turbulence intensity
$u^*$	Friction velocity
$\vec{R}_l$	Impulse force
$R$	Radius of a pipe
$U$	Streamwise mean velocity
$U_\infty$	Free stream wind speed
$f$	Darcy friction factor



## 1. Introduction

Measurement techniques that are typically used in turbulent flows to measure three components of velocities, turbulent stresses and turbulence intensities are Laser Doppler velocimetry, hot-wire velocimetry, Particle induced velocimetry. All these measuring instruments have disadvantages which concern high prices, complicated use and limited application. Cobra probe is a multi-hole pressure probe which design is based on a principle of operation of a Pitot-static tube. Chen, Haynes, Fletcher [2] indicate that the performance of a cobra probe in turbulent flows is not fully investigated and they recommend its investigation for more complex flows than turbulent pipe flow. The reasons to test out and suggest implementation of a cobra probe in these flows are its ease of use and wide range of its application. Hot-wire is not appropriate for industrial application and LDV has a limited range of working media [7]. According to Hooper and Musgrove [1] cobra probe is suitable for measurements in complex turbulent flows because of its frequency response. However, they found out that cobra probe showed some discrepancy in measurements compared with a hot-wire.

In this thesis, the goal is to investigate the performance of a cobra probe in a complex and time-varying flow. The main task is to find out if the values of errors in velocity, obtained by cobra probe in the condition of high ambient turbulence, fall within the limits of the uncertainty of  $\pm 0.5 \frac{m}{s}$  that is set by the manufacturer. The cobra probe's accuracy in measurements of turbulence intensity is not precisely determined, therefore the error of turbulence intensities should be also estimated. After analyzing the errors in the measurements, it is necessary to assess whether the cobra probe is a suitable measuring instrument for a complex turbulent flow or not.

To test out the performance of a probe two different flow cases were used. The first experiment was done for the turbulent pipe flow in which the measurements can be compared with the results from the previous studies. The second experiment took place in the recirculating wind tunnel with a grid placed at the entrance of its test section. The measurements were done simultaneously by cobra probe and LDV that were set 12 diameters downstream the wind turbine model. Measuring results obtained by cobra probe were compared with those obtained by LDV.

## 2. Theory

This section explains the basics of the turbulent flows that are investigated. Whether the flow is laminar or turbulent depends on the relative importance of fluid friction (viscosity) and flow inertia. The ratio of inertial to viscous forces is the Reynolds number (Re). For a circular pipe turbulent flow occurs at  $Re = \rho Vd/\mu \geq 4000$  [12]. For turbulent flows, 3 velocity components are presented.

### 2.1 Turbulence intensity

A velocity in turbulent flow varies in time due to the turbulent fluctuations. Thus, it is required for the instantaneous velocity component to be decomposed to time-averaged (mean) velocity component and fluctuation (time-varying velocity component).

$$u(x, y, z, t) = \bar{u}(x, y, z) + u'(x, y, z, t) \quad (2.1)$$

In the theory [4], the mean velocity can be evaluated through the integration:

$$\bar{u}(x, y, z) = \frac{1}{T} \int_0^T u(x, y, z, t) dt \quad (2.2)$$

Averaging period T must be chosen so that  $\bar{u}$  doesn't depend on time. The equation (2.2) is also applied for determination of  $\bar{w}$  -vertical and  $\bar{v}$  -lateral velocity component.

An impact of fluctuation velocities to the averaged velocity field can be explained through averaging the square of the velocity  $u$ :

$$\overline{u^2} = \frac{1}{T} \int_0^T u^2 dt = \frac{1}{T} \int_0^T (\bar{u} + u')^2 dt = \frac{1}{T} \int_0^T [\bar{u}^2 + 2\bar{u}u' + (u')^2] dt \quad (2.3)$$

Resolving the integrals from equation (2.3) following results are obtained:

$$\frac{1}{T} \int_0^T \bar{u}^2 dt = \bar{u}^2$$

$$\frac{1}{T} \int_0^T 2\bar{u}u' dt = \frac{1}{T} 2\bar{u} \int_0^T u' dt = 0 \quad \text{because} \\ \bar{u}' = 0$$

$$\frac{1}{T} \int_0^T (u')^2 dt = \overline{u'^2}$$



The result of the equation 2.3 is the new component  $\overline{u'^2}$  which is used for defining turbulence intensity. The overall turbulence intensity is defined as:

$$I_{\bar{u}} = \frac{\sqrt{\frac{1}{3}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})}}{\sqrt{\bar{u}^2 + \bar{v}^2 + \bar{w}^2}} \quad (2.4)$$

Turbulence intensity in the stream-wise direction is defined as:

$$I_{uu} = \frac{u'}{\bar{u}} \quad (2.5)$$

$u'$  is the standard deviation from the mean velocity. The turbulence intensity is typically given in percentages [%].

## 2.2 Turbulent pipe flow

A fluid in a pipe is considered entering a pipe at a uniform velocity. The velocity of the fluid particles in contact with a pipe wall becomes zero. The velocity of particles in the layers close to the wall gradually decreases because of the friction impact. To keep the constant flow rate the velocity at the center of the pipe increase. Gradually on that way, fully developed flow, where the velocity profile and temperature remain unchanged, is formed. The form of the velocity profile will depend on whether the flow is turbulent or laminar, the wall roughness and the pressure gradient. In this section, the main characteristics of the fully developed turbulent pipe flow will be explained.

### 2.2.1 Mean velocity profile

The velocity profile of the turbulent flow consists 3 layers:

- Wall layer- viscous shear dominates
- Outer layer-turbulent shear dominates
- Overlap layer-both types of shear are important

In the wall layer the velocity depends on wall shear, fluid properties and the distance from the wall.

$$\bar{u} = f(\mu, \tau_w, \rho, y) \quad (2.6)$$

It is scientifically proven that the velocity profile in the outer layer does not depend on viscosity. It does depend on the distance  $y$  from the centerline of the pipe where the velocity is maximum.

The velocity from the centerline decreases because of the impact of friction. Also, layer thickness has an impact on this deviation from the maximum velocity (U-stream velocity).

$$(U - \bar{u})_{\text{outer}} = g(\delta, \tau_w, \rho, y) \quad (2.7)$$

The wall layer and outer layer are merged. Thus, the velocity profile in the overlap-layer varies logarithmically with y:

$$\frac{\bar{u}}{u^*} = \frac{1}{k} \ln \frac{yu^*}{\nu} + B \quad (2.8)$$

Assume that equation (2.8) can be applied all the way of a pipe and introducing  $k=0.41$  and  $B=5$ , the following equation is numerically obtained in [3]:

$$\frac{V}{u^*} \approx 2.44 \ln \frac{Ru^*}{\nu} + 1.34 \quad (2.9)$$

In the equation (2.9) V is the average velocity from the velocity profile.  $V/u^*$  is related to the Darcy friction factor which is dependent on Reynolds number and roughness of the pipe:

$$\frac{V}{u^*} = \left(\frac{8}{f}\right)^{\frac{1}{2}} \quad (2.10)$$

The argument of the logarithm in (2.9) is equivalent to:

$$\frac{Ru^*}{\nu} = \frac{1}{2} Red \left(\frac{f}{8}\right)^{\frac{1}{2}} \quad (2.11)$$

[3]. From these correlations, it is simple to compute friction velocity  $u^*$  which is important in normalizing velocity profile in turbulent pipe flow.

## 2.2.2 Turbulent shear stress

Momentum transfer through a differential area ( $dA$ ) which is set tangential to the main direction of the flow explains the meaning of Reynolds shear stress.

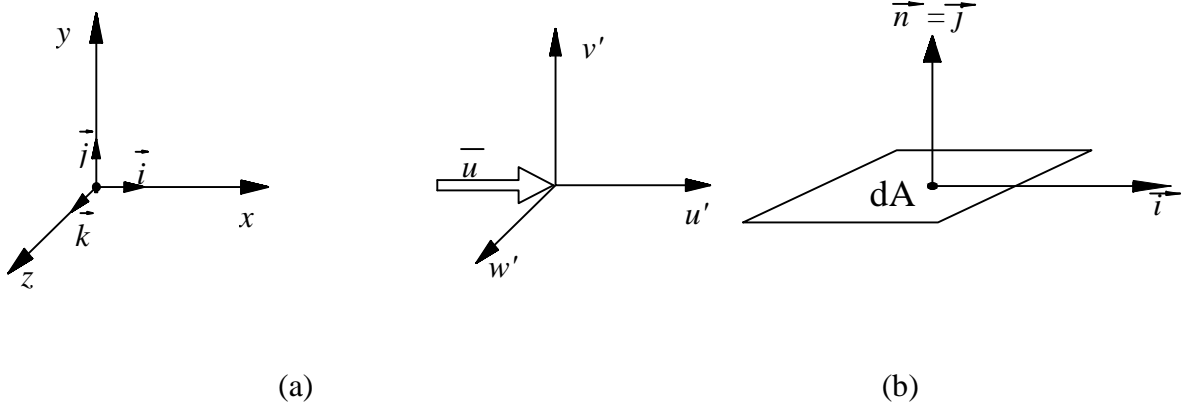


Figure 2.2: (a) model of 1D flow:  $u = \bar{u} + u'$ ,  $v = v'$ ,  $w = w'$ ; (b) differential area is tangential to the x direction,  $\vec{n} = \vec{j}$ , mean velocity  $\bar{u}$  is tangential to the differential area [4]

The impulse force defines momentum transfer:

$$\vec{R}_i = - \iint_A \rho \vec{u} (\vec{u} \cdot \vec{n}) dA \quad (2.12)$$

The equation (2.12) is then simplified:

$$\overline{dR}_i = -\rho \vec{U} (\vec{U} \cdot \vec{n}) dA \quad (2.13)$$

For the turbulent flow, instantaneous velocity is defined (Figure 2.2a):

$$\vec{U} = \vec{\bar{U}} + \vec{U}' = (\bar{u} + u')\vec{i} + v'\vec{j} + w'\vec{k} \quad (2.14)$$

As a differential area is set tangential to the main direction of the flow  $\vec{n} = \vec{j}$  (Figure 2.2b) and thus:

$$\left| \frac{dR_{i,x}}{dA} \right| = \rho uv \quad (2.15)$$

By time averaging of the component  $\rho uv$  an important relation is obtained:

$$\rho \bar{u}\bar{v} = \rho \overline{(\bar{u} + u')v'} = \rho (\overline{\bar{u}v'} + \overline{u'v'}) \quad (2.16)$$

Which leads to defining shear stress:

$$\rho \bar{u}\bar{v} = \rho \overline{u'v'} (u = \bar{u} + u', v = v') \quad (2.17)$$

Momentum transfer is done to the fluid particles that have lower mean flow velocity. Depending on whether a motion of fluid particles is upward or downward i.e. the motion takes place towards the positive side of y-axis or its negative side the signs of the fluctuating components  $u'$  and  $v'$  are determined. Thus, turbulent shear stress (Reynolds shear stress) is defined as:

$$R_{uv} = -\rho \overline{u'v'} \quad (2.18)$$

### 2.3 Wind turbine wake

The wind turbine wake is a complex flow which characteristics are still not completely investigated. The main features of the turbine wake are velocity deficit and increased turbulence. The velocity deficit is important in analyses of the wind turbine power while high turbulence intensities cause increased fatigue loads on downstream turbines [10]. The wind turbine wake is divided in two regions: near wake and far wake. The far wake is important for the wind farm performance analyses. That is the region that starts where the shear layer that is formed due to velocity differences in the wake and outside the wake is reaching the axis of the wake [11]. That happens typically at the distance of  $x/D=2-5$  rotor diameters where the near wake region ends [10]. High ambient turbulent conditions expedite the wake recovery. These conditions can be simulated in the laboratory involving a grid which generates free stream turbulence.

### 3. Experimental setup

This section explains the setup for the pipe flow and wind turbine wake measurement experiments. In both experiments, cobra probe hardware was connected to the A / D converter that was connected to PC which had TFI software installed. TFI software allowed all data to be obtained in appropriate units of measurement (m/s for velocities, % for turbulence intensities, Pa for turbulent stresses etc.). When analyzing the data obtained with the cobra probe the coordinate system in which it operates was considered. The probe resolves three components of velocity- longitudinal  $u$ , lateral  $v$  and vertical  $w$ . In both experiments, the sampling frequency of the signal was set high enough to avoid aliasing using the Nyquist-Shannon sampling theorem [14]. Calibration of the cobra probe is already done by the manufacturer. Cobra probe was ‘zeroed’ before using to remove offset voltages from the pressure transducers. ‘Zeroing’ should be done while the flow is stopped [15]. The statement considered during the experimental setup is that cobra probe can’t provide good measurements in a reversed flow [7]. Very small measuring uncertainty of LDV which is about  $\pm 0.01 \frac{m}{s}$  [13] was not considered in following analyses and thus disagreement between the results of cobra probe, which has much higher measuring uncertainty, and LDV was defined as an error of cobra probe.

#### 3.1 Turbulent pipe flow experiment

The pipe was smooth, with a diameter of 180 mm and a length of 83 diameters. The coordinate system used in the pipe has its reference ( $z=0$ ) on the center line of the pipe. The measurements were done at the horizontal line of the pipe diameter. Cobra probe was set 10mm downstream from the pipe exit. The Reynolds number of the flow was 110 455. 50000 samples measured with the probe were collecting at every measuring point. The measurements were first done by pitot probe and then by cobra probe. The measuring results of mean velocity obtained by cobra probe will be compared with the results of pitot probe. The interest for such comparison stems from the similar principle of operation of these two measuring instruments described in detail by B. O. Johnson [9]. This experiment presents an initial test of cobra probe's performance in a turbulent flow because the results can be also compared with those that were obtained in previous studies.

### 3.2 Wind turbine wake measurements setup



*Figure 3.2: The setup of the equipment in the wind tunnel*

The test section of the wind tunnel is 1.8m high, 2.7m broad and 11m long. The turbine with a rotor diameter  $D=0.45\text{m}$  was installed at the distance  $2.71D$  downstream of the inlet of the wind tunnel. The freestream velocity ( $U_\infty$ ) was selected to be  $10.3\text{ m/s}$ . To obtain high turbulent condition, the grid was set at the inlet of the wind tunnel. The grid had square holes of  $192\text{mm}$  and a mesh size of  $240\text{mm}$ , providing a uniform flow profile. The measurements were taken with LDV and cobra probe that were set on the computer controlled traverse mechanism. LDV and cobra probe were distanced at  $60\text{mm}$ . Such setup was made in order to provide unobstructed measurements by both of devices at the same time. Cobra probe's dimensions are significantly smaller than LDV's, thus it is important to be distanced enough from LDV. Also, on this way the measuring data analyzing is simplified as the measurement was done for the full wake with the increments of  $60\text{mm}$  in  $y$  and  $z$  directions. Two-dimensional full wake in the  $zy$ -plane was measured at distance in the  $x$ -direction of  $12D$  behind the turbine.  $247$  points were investigated instead of  $357$  points that the grid is consisted of, because of the breakdown of the traverse during the measurements in the remaining positions.  $50000$  samples measured with a cobra probe were collected at every measuring point.

## 4. Results and discussion

### 4.1 Turbulent pipe flow

#### 4.1.1 Mean velocity profile

Figure 4.1 shows the comparison between mean velocity profile of pitot probe and cobra probe. The disagreement between these two measurements is from 0.12 m/s to 0.22 m/s except close to the pipe walls where the high velocity gradient causes the error. The velocity at the center of the pipe measured by pitot probe is 10.34 m/s and measured by cobra probe is 10.47 m/s. The mentioned disagreement falls within the limits of cobra probe's uncertainty of  $\pm 0.5 \frac{m}{s}$ .

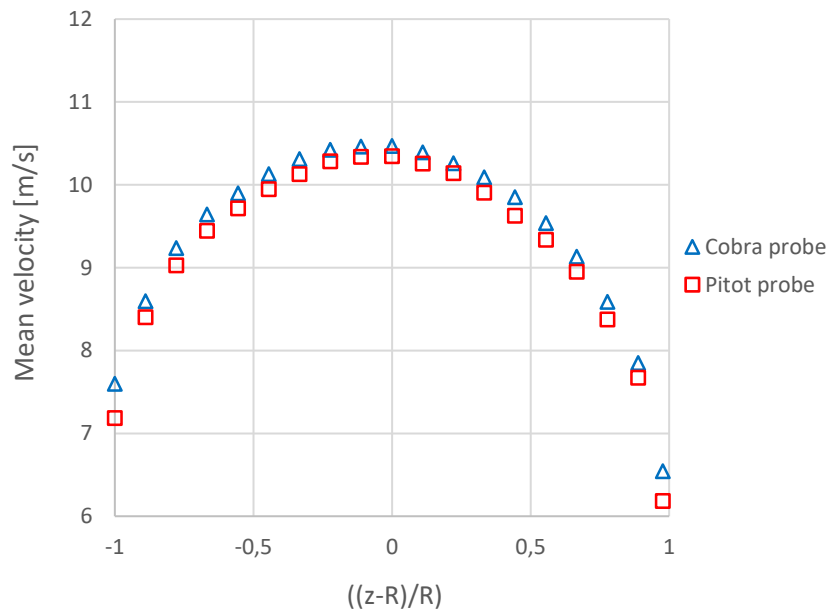


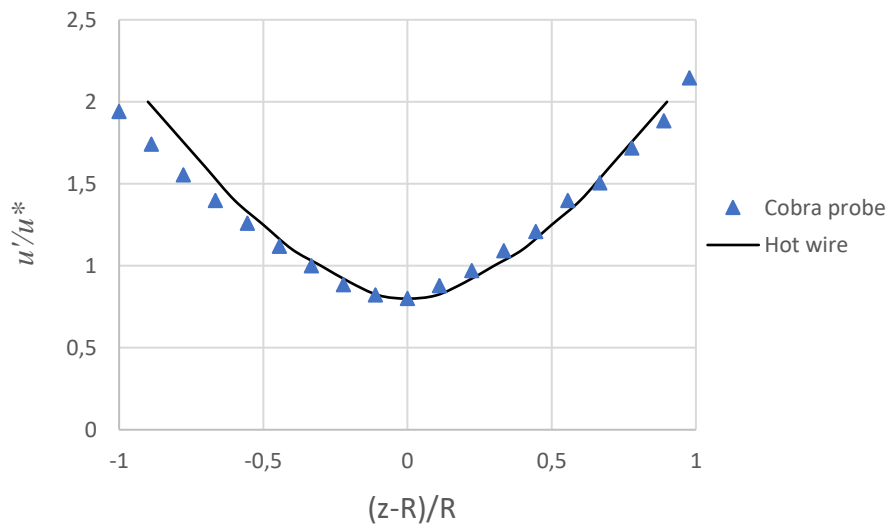
Figure 4.1: Mean velocity profile for a turbulent pipe flow

It was already shown, in some previous studies done by Mallipudi, Selig [5] that the velocities measured by cobra probe and pitot probe were similar in magnitude, but could not reach the complete agreement. Measuring the velocity range from 0 to 15 m/s they found out that discrepancy in velocity of these two measuring instruments depends on speed and was found to be bigger at low speeds.

Cobra probe resolves the velocities within the half of the range  $\pm 45^\circ$ . For the highly accurate measurements, cobra probe should be aligned to the flow direction. Misalignment of a cobra probe leads to errors in measurement. The value of yaw angle determines the alignment. The error in yaw angle of  $2^\circ$  doesn't affect mean velocity and turbulence stress results, but produces the error in tangential velocity [2]. In this experiment cobra probe was well adjusted, so this error source can be excluded for this case.

### 4.1.2 Turbulence intensities

Axial, radial and tangential turbulence intensities ( $u'$ ,  $v'$ ,  $w'$ ) normalized by the wall friction velocity ( $u^*$ ) are shown in Fig. 4.2 (a-c). In the previous examples of measurements that were done with a cobra probe by Hooper and Musgrove [1][6] for the different Reynolds number can be noticed that distributions of turbulence intensities, when normalized with a friction velocity show the high level of similarity. The Reynolds numbers in these examples were 178000 and 196000. This leads to the conclusion that Reynolds numbers effect can be neglected in the following analyses. In the Figure 4a is presented the axial turbulence intensity distribution obtained through the measurements with a cobra probe and compared with the hot-wire's results presented by Hooper and Musgrove [1].



*Figure 4.2(a): Axial turbulence intensity  $u'$  normalized by the friction velocity  $u^*$*

Cobra probe's results for the axial turbulence intensity show agreement with the hot-wire's results. It can be noticed that there is discrepancy in distribution close to the pipe wall. This is due to the lack of symmetry in distribution with respect to the pipe center line. Figure 4.2(b) presents radial turbulence intensity which shows higher discrepancy between the results of cobra probe and hot-wire.



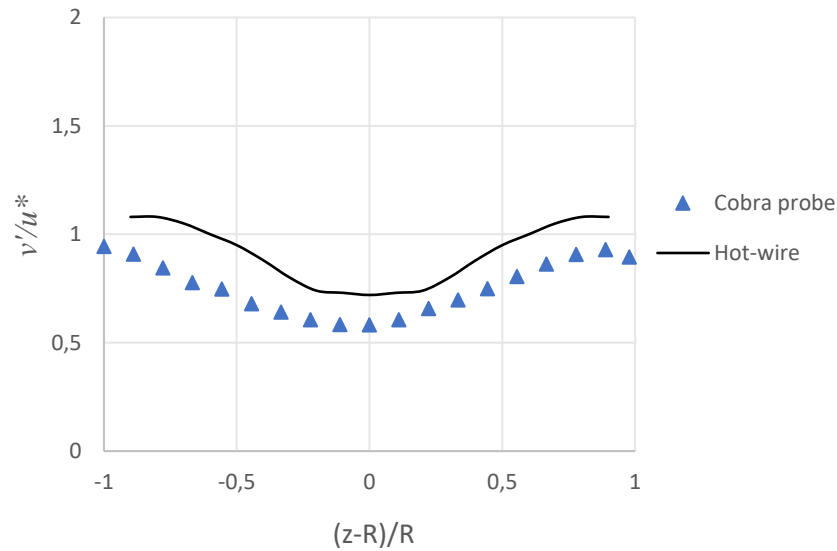


Figure 4.2(b): Radial turbulence intensity  $v'$  normalized by the friction velocity  $u^*$

Cobra probe's data are about 15% lower in magnitude than hot wire data. Figure 4.2(c) shows tangential turbulence intensity where is also noticeable the discrepancy of about 15%-20% in magnitude.

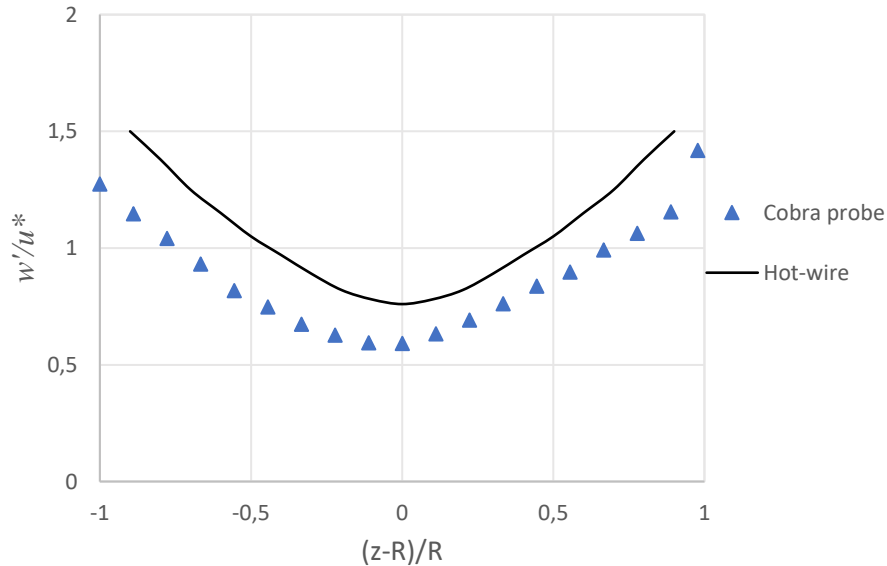


Figure 4.2(c): Tangential turbulence intensity  $w'$  normalized by the friction velocity  $u^*$

Disagreement in magnitude is bigger approaching to the wall of the pipe. The distribution is not symmetrical with respect to the pipe center.

### 4.1.3 Turbulent shear stress

Turbulent (Reynolds) shear stress  $R_{uv}$  when normalized with wall shear stress should have distribution of values from -1 to 1. This distribution should be linear function in respect to the distance from the pipe wall [1].

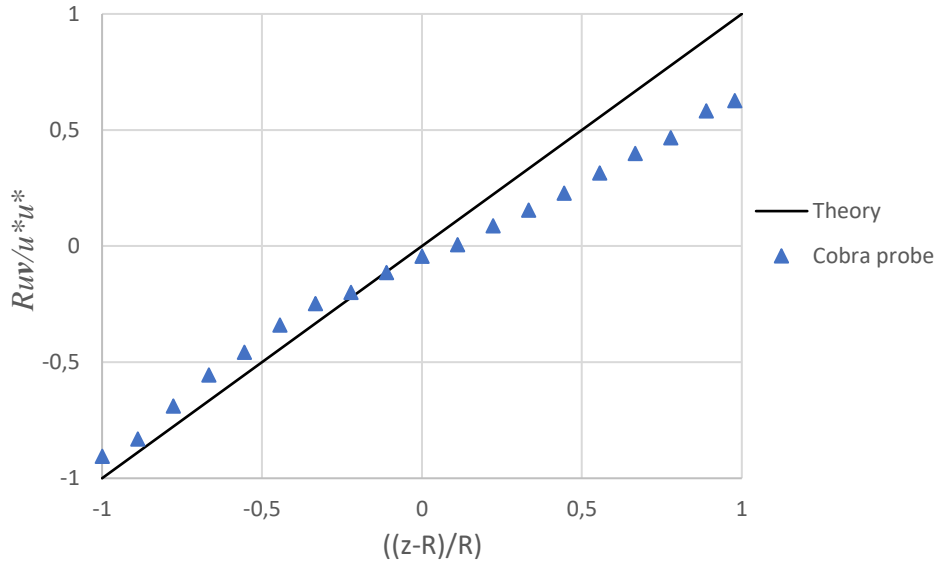


Figure 4.3: Turbulent shear stress distribution for a pipe flow

Cobra probe didn't achieve linearity as can be seen from the figure 4.3. For the values of  $((z-R)/R) < 0$  distribution of Reynolds shear stress is similar to the Theory. The value of Reynolds shear stress close to the pipe wall is -0.9. At the center line of the pipe  $R_{uv}/u^*u^*$  is almost zero. It was observed by Hooper and Musgrove [6] that cobra probe couldn't resolve the components of turbulent shear stress in the wall region. In the example that is presented in Figure 4.3, the influence of the wall region to the distribution of Reynolds shear stress can't be noticed. This is attributed to the fact that the cobra probe was set at the distance outside the wall region which thickness is much less than 1% of the pipe diameter [12].

## 4.2 Turbine wake measurements

### 4.2.1 Velocity deficit

The difference between mean axial velocities measured by a cobra probe and LDV normalized with the freestream velocity is presented in Figure 4.4.

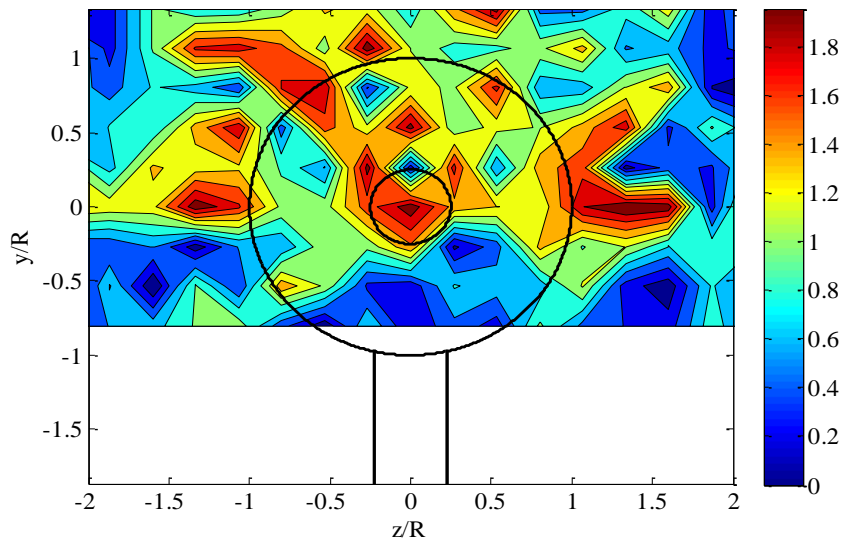
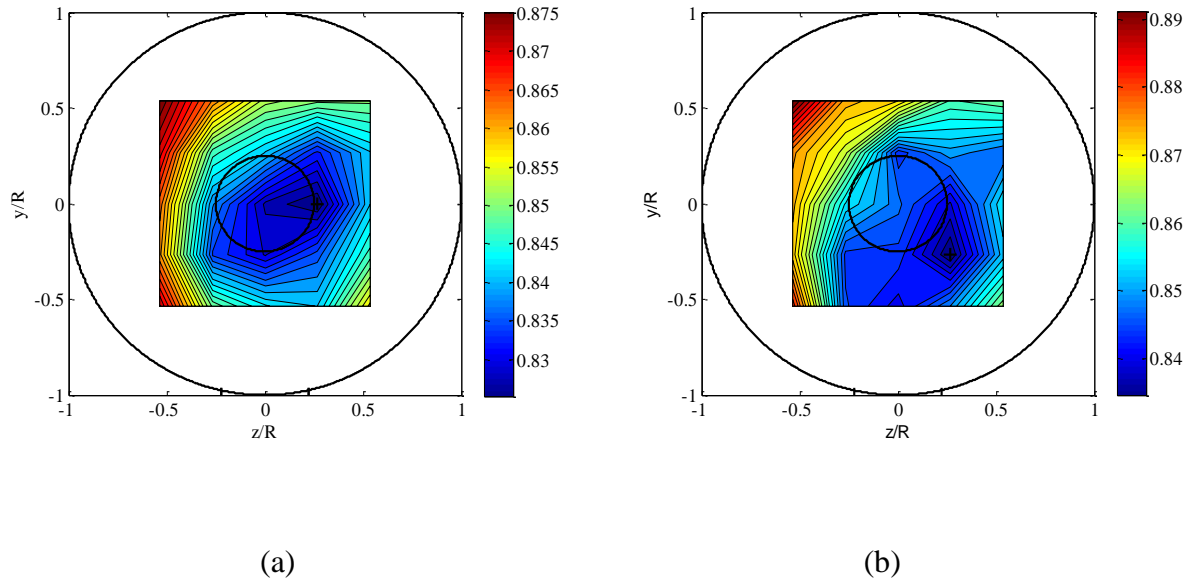


Figure 4.4: Cobra probe's error of mean velocity normalized by freestream velocity

$$|(U_{M(\text{cobra probe})} - U_{M(\text{LDV})})| / U_{\infty} [\%]$$

The color bar range of error for velocity measured by cobra probe goes from zero to about 2% with dark blue corresponding to zero error and dark red corresponding to an error of 2%. The maximum error is found at the hub height. This is the area where is recorded the largest number of disagreements with the results obtained by LDV. High pitch and yaw angles that can be a source of the error are not present in this case. The error of 2 % is present at some random places behind a turbine, but not as a set of values like it is the case at the hub height. This will result in that the center of the wake measured by a cobra probe won't be recorded at the hub height which is expected for the experiments with a high ambient turbulence [8]. The center of the wake obtained by the cobra probe's measuring data is shifted down. It is defined where the lowest velocities were found and is marked with a symbol (+) on figure 4.5(b).



*Figure 4.5: Two-dimensional velocity wake under high ambient turbulent conditions, centered on the rotor axis 12D downstream the turbine. The plus sign (+) in the plot marks the center of the wake (a) LDV results of the velocity deficit  $U_M/U_\infty$  (b) cobra probe results of the velocity deficit  $U_M/U_\infty$*

Cobra probe shows smaller velocity decay in respect to the LDV results. This can be attributed to fact that cobra probe mainly recorded higher velocities than LDV. The complete agreement between velocities is rare. This could relate to the comparison between mean velocity distribution of cobra probe and pitot probe (Figure 4.1). In both cases cobra probe shows an offset respect to the values obtained by the reference device. In the case of turbine wake measurement this offset varies more than in the case of pipe flow where the disagreement varies from about 1% to 2%.

It should be mentioned that the cobra probe was ‘zeroed’ before using and few times during the measurement. This experiment included measurements at many positions, thus TFI software proposed ‘zeroing’ many times during the experiment. ‘Zeroing’ involves stopping the flow and therefore restarting the engine of the wind tunnel to reach the required speed. For this reason, it was not convenient to do that frequently.

## 4.2.2 Turbulence intensity

The agreement between the results of turbulence intensity obtained by cobra probe and LDV is shown in Figure 4.6.

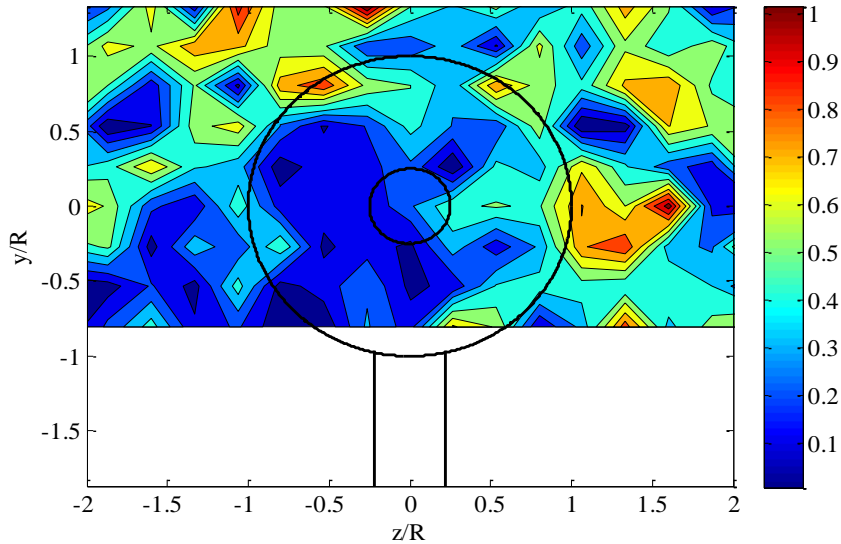


Figure 4.6: Cobra probe's error of turbulence intensity

$$\Delta I_{uu} = |I_{uu}(\text{cobra probe}) - I_{uu}(\text{LDV})| [\%]$$

The color bar range of error for turbulence intensity measured by a cobra probe goes from 0% to about 1%, with dark blue corresponding to zero and dark red corresponding to 1%. The errors in mean velocity can't be considered as an impact to the errors in turbulence intensity even though there is a relation between mean velocity and turbulence intensity explained in section 2.1. The biggest errors in mean velocities are recorded behind turbine rotor, but the error of turbulence intensity in this area is less than 0.4 %. It can be observed in figures 4.7 and 4.8 that cobra probe gives the results of more uneven distribution of turbulence intensity than LDV. Relative to the  $z/R=0$  position from  $z/R=-1$  to  $z/R=1$  LDV shows more symmetry in turbulence intensity distribution than cobra probe. Both of them show high turbulence intensities with a bigger range on the positive side of  $z/R$  axis than on its negative side. It can be also noticed that cobra probe shows smaller values of turbulent intensities regarding LDV. This example of turbulence intensity distribution can be related to pipe flow experiment (Section 4.1.2) where the lack of symmetry and disagreement in values of turbulence intensity were observed.

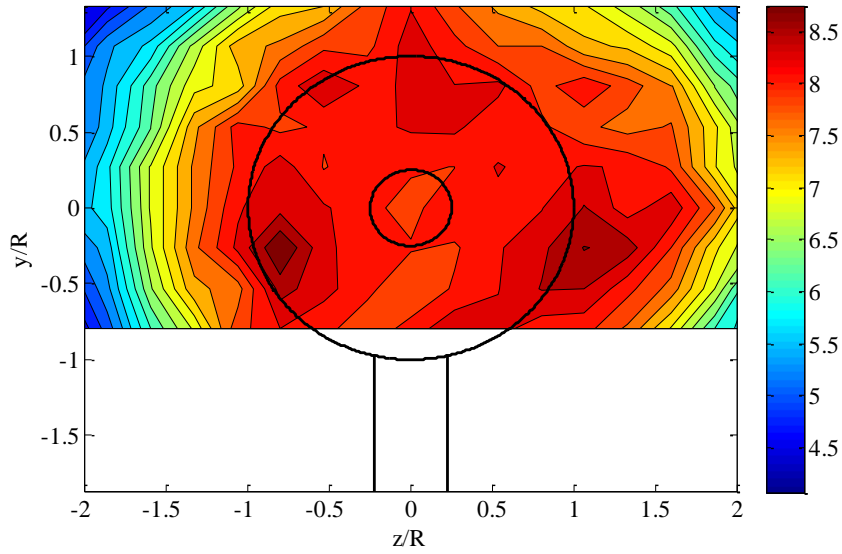


Figure 4.7: Turbulence intensity profile of the wake under high ambient turbulent conditions, centered on the rotor axis 12D downstream the turbine measured by LDV

$$\text{Turbulence intensity-}I_{uu} = u'/U_m [\%]$$

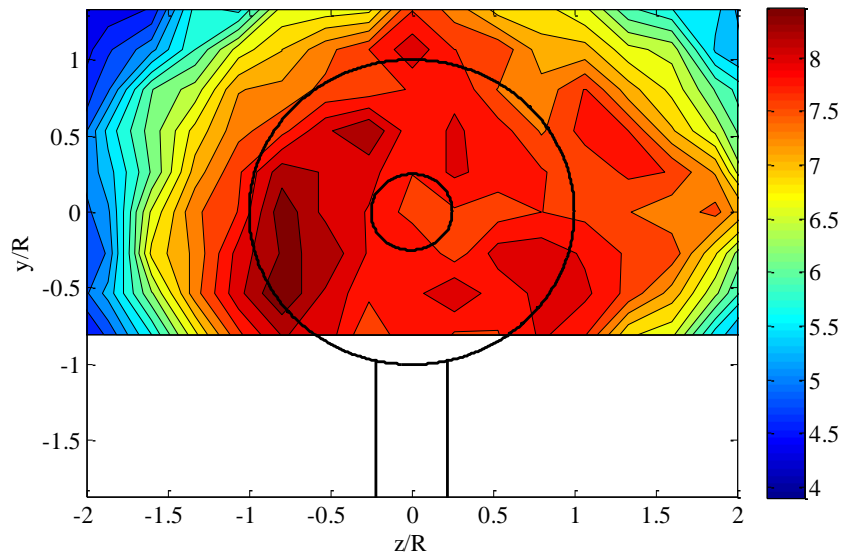


Figure 4.8: Turbulence intensity profile of the wake under high ambient turbulent conditions, centered on the rotor axis 12D downstream the turbine measured by cobra probe

$$\text{Turbulence intensity-}I_{uu} [\%]$$

## 5. Conclusion

The performance of the cobra probe in a complex flow with an increased turbulence level was investigated in this thesis. Cobra probe couldn't provide precise results in the mean velocity as LDV. Based on results that were analyzed in the previous chapter it is expected for the measuring uncertainty of mean velocity to be about 2% for the wind speed of about 10m/s under conditions of high ambient turbulence. Turbulence intensity results were not affected by the errors in mean velocity. The maximum error in turbulence intensity was found to be about 1%, but mostly the error value was up to 0.6%. From the results of the pipe flow experiment, lack of symmetry in turbulence distribution was noticed and was also found in results for the turbine wake measurements.

Cobra probe showed to be a suitable measuring instrument for measurements in a complex turbulent flow, especially for the measurement of turbulence intensity. The errors in axial mean velocity were within the limits of manufacturer's uncertainty.

In this thesis, the mean velocity and turbulence intensities values were observed because these components are most important in the far wake analyses which is important for the studies of the wind farm performance. For the complete evaluation of cobra probe's performance and for suggesting its implementation in a wider range of application, it was required to do the measurements of Reynolds shear stresses, simultaneously with the probe and LDV and compare these results.

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