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Nominal Wake Measurements by LDV
Model Scale Experiments

1.   PURPOSE OF PROCEDURE

The purpose of this document is to provide guidelines to ensure the best possible test results in terms of accuracy and reliability of a flow survey of the nominal wake at the propeller disk of a ship model utilizing Laser Doppler Velocimetry (LDV).

Generally these guidelines can also be applied to any flow survey, which uses LDV.

2.   PARAMETERS

2.1   Definition of Variables

f_{Doppler}	Doppler frequency
m_i	Weighting coefficient to correct the LDV velocity bias
q	Turbulent kinetic energy
R	Propeller radius
T_V	Turbulence Intensity
Δt_i	Time interval between the i velocity sample and the i-1 sample
$0, X.Y, Z$	Cartesian reference system with origin in the propeller disc, X axis parallel to the shaft line in downstream direction, Y from port to starboard direction, Z
V	Generic velocity component measured by the LDV system
$\overline{V}$	Mean velocity
V_i	Generic LDV velocity sample
$V_i^{'}$	Velocity fluctuation from the mean velocity
α	Angle between the laser beams
λ	Light wavelength
σ_V	Velocity standard deviation
ω_x	Vorticity

3.   NOMINAL WAKE MEASUREMENT

A nominal wake test consists in measuring the velocity distribution at the propeller disk. This testing can be performed using different measurement techniques such as Pitot tube rakes, 5-hole probes, hot films and Laser Doppler Velocimetry. The present procedures deal with the application of LDV to this problem.

The main advantages in using LDV are:

- it is linear and non-intrusive,
- the calibration is simple and depends only on optical parameters,
- it is suitable for the simultaneous measurement of the 3-velocity components at a point,
- it is able to measure the flow direction and hence to resolve detached flow,
- it is able to resolve velocity fluctuations up to a frequency content of some kHz,
- it is suitable for the measurement of high order statistic, such as Reynolds stress tensors.

The main limitations in using LDV are:

- the flow has to be correctly seeded with particles that might be a pollution source

of the facility specially for cavitation tunnel,

- the length of the measuring volume along the axis of the beams is quite large (about 5mm up to 10mm); the measurement is then an spatial integration of the local flow velocity. Moreover the positioning along this axis using pinhole is not very accurated (about of half the length of the measuring volume.

Different types of facilities can be used for this type of testing, including towing tanks, free surface cavitation tunnels, circulating water channels, cavitation tunnels, as long as they allow the installation of a complete scaled ship model.

3.1 Model and Instrument specifications

3.1.1 Ship Model requirements

A full ship model is required for the measurement of the nominal wake at the propeller plane. The specifications for the ship model should comply with the dedicated procedure in the ITTC 7.5 01-01-01 Quality Manual. In addition to those specifications, any potentially exposed surface to the laser light (e.g. shaft, brackets, boss hub cup, propeller, hull) should be painted flat black to reduce light reflections. This specifically is addressed to the operating safety and the improvement of the Signal to Noise Ratio (SNR) of the Doppler signal.

The ship model should be equipped with all the required appendages, fin stabilizers, and turbulence stimulators that can influence the propeller inflow. Only the rudder can be removed to allow easier optical access of the LDV system to the propeller disk.

The positioning of the measurement volume is of critical importance. Small targets are required for the alignment of the LDV measurement volume to the ship model. Each target consists of a small brass plate (Figure 1) with the following geometric characteristics:

- about 1 mm thickness,
- rectangular surface ranging from, about 5x5 to 15x15 mm^2,
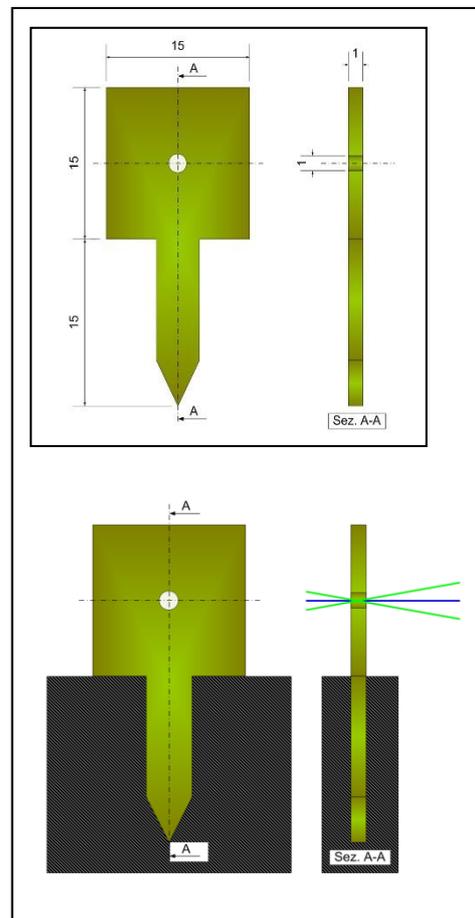- 1 mm diameter circular hole in the center.

Figure 1: LDV target alignment

The passage of all the laser beams of the LDV probe through the hole assures that the measurement volume is at a known position.

Target positioning should be performed in the shop in order to assure high level of accuracy in defining their locations in the ship model reference frame. In addition, the positions of the targets must be such to be reached by the LDV probe installed in the traversing system, downstream the measurement plane possibly.

For the case of the wake survey at the propeller disk a valid solution is to install the targets on the hub cup (Figure 2).
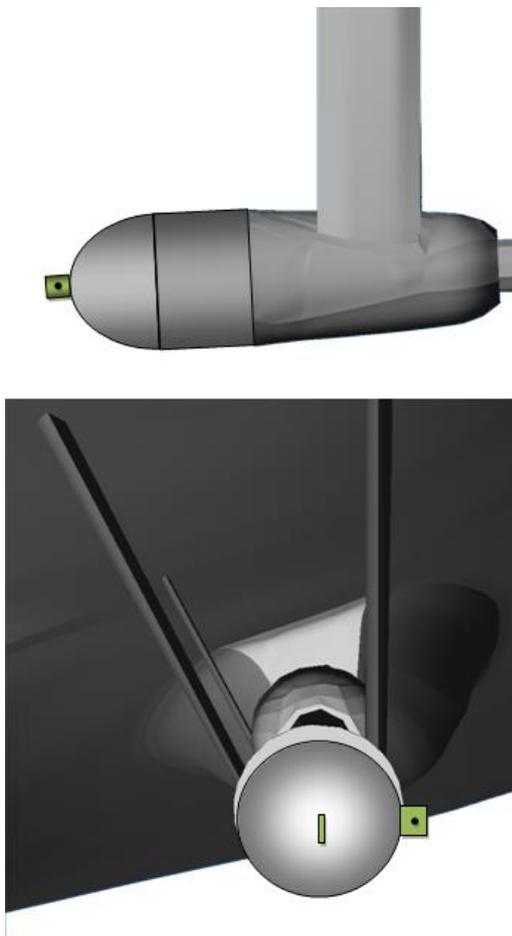

Figure 2: Target installation on the hub cup

For the axial wake survey 2 alignment targets are required typically, two optical configurations of the LDV probe being necessary to scan the propeller disk area completely.

3.1.2 LDV System Specifications

A one or two component (1C, 2C) underwater LDV system is required for the nominal wake survey. Indeed such a system shall be preferred to the one with 3 components because it allows for easier optical access to the whole propeller disk.

The measurement of the 3-velocity components can be performed with 1C or 2C LDV system in successive steps by sweeping the measurement grid.

Underwater optical fiber probes are available on the market. The probe should be streamlined to limit its perturbation as much as possible. The focal length of the optical lens should be such to allow for measurement from a distance such to minimize probe interference at the measurement point.

In this regard, the focal length equal to at least 6 probe diameters is recommended.

3.1.3 Traversing Mechanism

The probe shall be supported by a fin strut to be mounted on a three degree of freedom remotely controlled traversing mechanism that should allow the displacement of the measurement volume within an accuracy of $1/10^{th}$ of mm.

The alignment of the LDV probe to the direction of the propeller shaft requires the traverse system to be equipped with a device that allows the small rotations of the strut fin in the vertical plane within the range $\pm5°$.

Probe fixing on the strut fin has to be carried out with care in order to get the optical axis of the probe aligned with the horizontal direction, with the minimum error. This operation can be performed very easily and with a high level of

accuracy aligning the LDV probe to a horizontal plane by a level arm and projecting the beams on a flat plane at least 3m away from the probe. The probe is then rotated, in order to align the laser beam, which measures the axial component, to the horizontal by a level arm. Once this procedure is carried out, the LDV probe can be aligned to the direction of the propeller shaft. The mechanical design of the fin strut and the traversing mechanism should minimize strut deformation as much as possible.

A manual remote control is required to align the LDV measurement volume with the alignment target.

3.1.4   LDV system calibration

The most interesting aspect of the LDV technique is that it is linear and the calibration of the system depends only on the optical parameters of the transmitting lens (in particular, the angle α of the beams forming the measurement volume) and on the light wave length λ:

$$V = \frac{\lambda}{2\sin(\alpha/2)} f_{\text{Doppler}}$$

where f_{Doppler} is the frequency shift of the light due to the Doppler effect and V is the component of the velocity in the plane of the laser beam perpendicular to the bisector of the laser beam angle.

Hence calibration can be performed very easily and with a high level of accuracy by projecting the beams on a wall and measuring the distances between the measurement volume and the traces of the laser beams.

Calibration is maintained until the probe beams need to be realigned for maintenance purpose.

To really follow a Quality System, the calibration of the calculation of the velocity $V = f_D \cdot d_f$ should include both the calibration of :

1) The calibrating the frequency processed by the Burst Signal Analyser

The calibration of the Burst Signal Analyser (BSA) is done using a reference frequency generator that simulates a Doppler signal within frequencies from 30 MHz up to 50 MHz. The Doppler frequency of the analyser is compared with the frequency set on the generator. The uncertainty should be as written on the graph hereafter for a confidence interval of 95% .
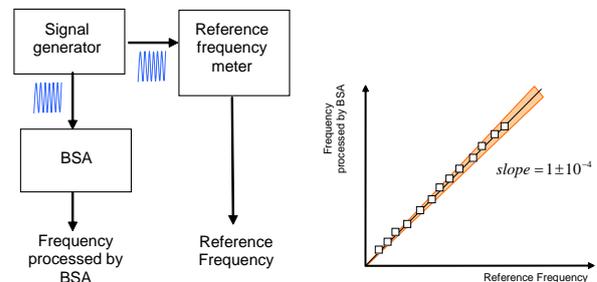

Figure 3: Calibration of the frequency processed by the BSA

Although the order of magnitude is rather small ($\frac{\Delta f_D}{f_D} \approx 10^{-4}$), it should be checked time to time.

2) Calibrating the fringe spacing with the rotating disk

The calibration of the fringe spacing is implicitly done by the speed calibration using a rotating disk with a known diameter (for example D= 0.15m ± 2 x 10-5) and a known revolution rate within the range of 2 Hz–40 Hz (uncertainty of 50 µHz).
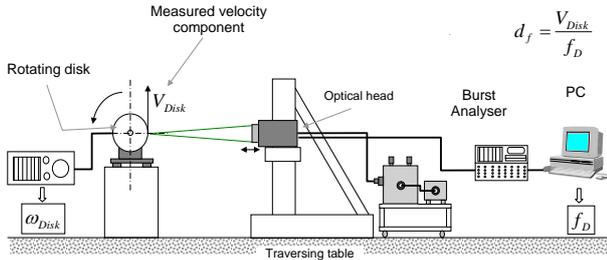
Figure 4 : Calibration of the fringe spacing using a rotating disk

The fringe spacing is then calculated using the revolution rate of the disk along with its diameter and the measured frequency by the calibrated BSA :

$$d_f = \frac{V_{Disk}}{f_D} = \frac{(D_{Disk}/2) \cdot \omega_{Disk}}{f_D}$$

This fringe spacing is assessed for different positions of the disk along the main axis of the probe volume. The calibration of the fringe spacing is defined for the position that gives the maximum data rate.

The final error on the fringe spacing calibration is then calculated from :

1) the diameter uncertainty, the disk revolution rate uncertainty,
2) the Doppler frequency uncertainty,
3) and the uncertainty on the fringe spacing coming from the variation of the fringe spacing measured for different positions of the disk along the main axis of the probe volume. This variation causes the major uncertainty.

In the end, we got an uncertainty on the fringe spacing which is of the order of magnitude:

$$\frac{\Delta d_f}{d_f} \approx 1 \cdot 10^{-2}$$

3) Velocity uncertainty

From the previous uncertainties on the Doppler frequency measured by the BS and on the fringe spacing measured using the rotating disk, the uncertainty of the velocity

$$\frac{\Delta V}{V} = \frac{\Delta f_D}{f_D} + \frac{\Delta d_f}{d_f} \approx 1 \cdot 10^{-2}$$

3.2 Test setup

3.2.1 Model

The model should be locked at the dynamic trim, measured in the self propulsion test for the adopted test condition before. The model support should be as rigid as possible, because any model deformation results in positioning errors of the measurement volume relative to the model and an increased error in the wake measurement.

3.2.2 Measurement Grid

Typically nominal wake measurements are made by Pitot rakes mounted on the hub, which forces the use of a polar measurement grid. It turns out that this measurement grid is useful in the harmonic analysis of the wake. However, the consequence of non-uniform spatial sampling rate is not optimal for capturing flow structures, due to the very narrow measurement spacing in the inner radius of the propeller and very coarse spacing at the outer radius.

The use of LDV allows for the removal of the mechanical constraint of using a polar measurement grid and a Cartesian grid is preferred.

Furthermore, refined grids with higher spatial resolution are required to resolve flow regions with high gradients.

An example of this case is the twin screw ship measurement grid, shown in Figure 3, which has been concentrated in the regions behind the shaft brackets.

The measurement grid shall extend, up to *r/R*=1.05 at least.

The point-to-point distance should comply with the Nyquist criteria and thus be at least less than ½ of the dimension of smallest flow structure present in the wake to be resolved. This results in measurement grids with more than 250 points typically.

3.2.3 LDV system optical configurations

Three optical configurations are required to obtain all the velocity components at the propeller disk when a 2C LDV probe is used (Figure 6). The first two configurations are required to acquire the axial velocity over the entire measurement disk. The third configuration is required for the measurement of the cross-flow components.

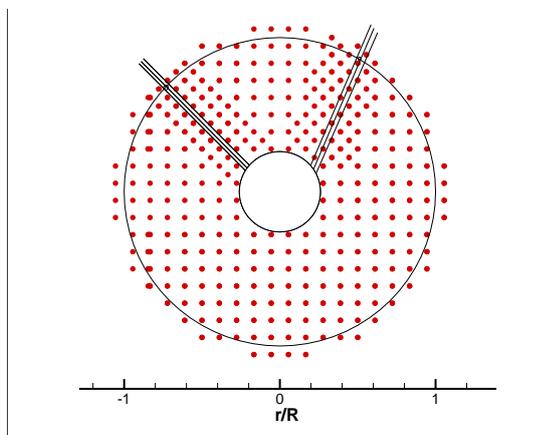Each optical configuration requires an alignment target to minimize the positioning error.

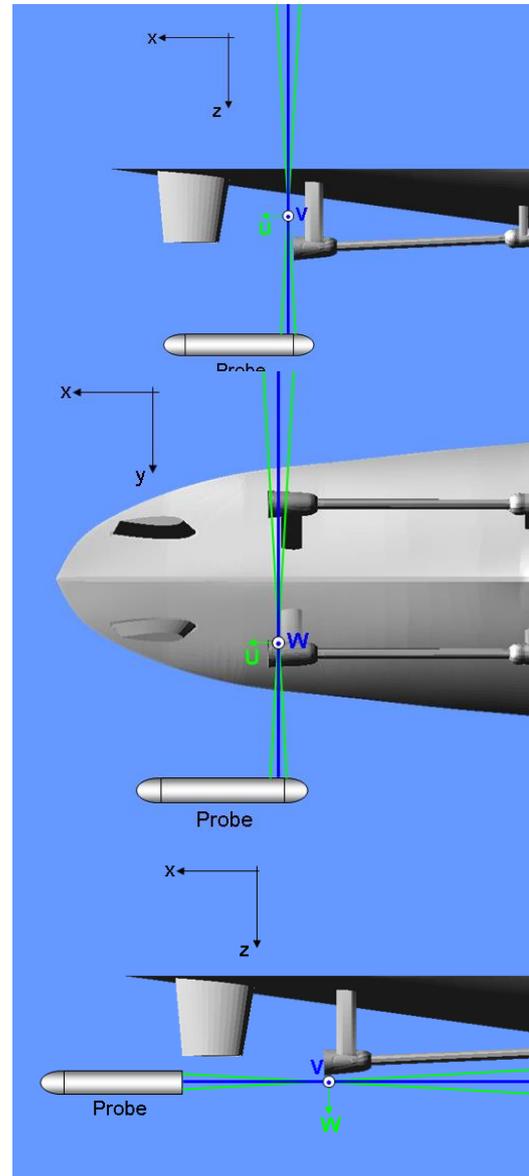Figure 5: Example of measurement grid at the propeller disk for a twin screw ship

Figure 6 : Different LDV optical configurations required to sweep the whole propeller disk and needed for measuring the three velocity components

3.2.4 LDV system performance

The LDV system should guarantee a minimum performance of 100-200 samples/s at least.

This performance depends on many parameters, like the focal length, the optical power of the laser beams, the quality of the alignment, the quality and concentration of the water seeding.

The fulfillment of a suitable water seeding depends on the facility type and is more difficult in a towing tank where the flow has to be seeded in order to assure a minimum performance of the LDV system (see § 2.2.6).

3.2.5   Particle seeding

Normally in water application particle seeding is not a difficult problem to solve. In model ship wake measurements the velocity lag between the flow and the particle can be ignored. In case it is necessary to seed the flow, titanium dioxide can be used as valid and inexpensive solution. Other materials that can be used for seeding the flow are hollow glass sphere, polystyrene beads, etc. Any seeding device (typically a rake) should distribute the seeding particles uniformly, introducing as little flow disturbance as possible. In towing tanks any seeding device could be placed behind the model and the flow seeded in the return run of the carriage.

4.   LDV DATA PROCESSING

LDV data provides uneven spaced time history of the velocity at a point due to the random sampling of velocity as the consequence of the random crossing of a particle in the measurement volume. These data can be used to evaluate mean and fluctuating flow characteristics, but also other turbulent quantities of interest, such as the turbulent intensity.

The drawbacks of non-uniformly spaced time histories have been widely studied in literature. In this regard, bias and dedicated algorithms for signal processing can be found in the literature.

In the following section the main first (mean) and second order (turbulent intensity) statistical estimators are reported. The time length of the acquired time series shall guarantee the convergence of both the statistical estimators. This shall be verified in the region of high turbulence level.

4.1   Statistical processing

The LDV technique provides a series of velocity data V_i acquired at randomly spaced interval time Δt_i (time between the actual data sample and the previous one)

Following the typical approach of turbulent flows, and using the Reynolds decomposition, the velocity field can be decomposed in a mean ($\overline{V}$) and in a fluctuating component ($V_i^{'}$), as follows:

$$V_i = \overline{V} + V_i^{'} \tag{1}$$

The mean value is defined by:

$$\overline{V} = \frac{1}{N} \sum_{i=1}^{N} V_i \tag{2}$$

where N is the number of acquired samples.

In LDV, the measurement is performed on individual particles as they traverse the measurement volume. It is quite clear that more particles will traverse the measurement volume per unit of time as the velocity increases. In fact, the flux of particles in the measurement volume is proportional to the velocity. Therefore, if a simple average of the individual measurements is being made, the result will be biased to the high velocity side, since there will be more measurements per unit of time at the higher velocities.

Several solutions have been proposed in literature to solve the problem of the velocity bias in the LDV acquisition (i.e. inter-arrival time weighting, transit time weighting).

The formulation of the mean velocity that accounts for the bias correction is reported in (3):

$$\overline{V} = \frac{\sum_{i=1}^{N} m_i V_i}{\sum_{i=1}^{N} m_i} \qquad (3)$$

where N is the statistical population (i.e. number of velocity samples) and m_i the weighting coefficient. The expressions of the weighting coefficient in case of inter-arrival time weighting and transit time weighting is reported hereinafter:

- inter-arrival time weighting $\quad m_i = \dfrac{1}{\Delta t_i}$

- transit time weighting $\quad m_i = \dfrac{1}{V_i}$

An estimation of the velocity fluctuations can be provided by considering the standard deviation of the velocity signal σ_V. The unbiased relation is given by:

$$\sigma^2{}_V = \frac{\sum_{i=1}^{N} m_i (V_i - \overline{V})^2}{\sum_{i=1}^{N} m_i} \qquad (4)$$

Turbulence levels can be calculated and expressed in percentage of the forward speed of the ship model U. by using the following expression:

$$T_V = \frac{\sigma_V}{U} \cdot 100 \qquad (5)$$

Another and equivalent representation of the 2nd order statistics can be the turbulent kinetic energy q defined by:

$$q = \frac{1}{2} \sqrt{\sigma^2{}_{V_x} + \sigma^2{}_{V_y} + \sigma^2{}_{V_z}} \qquad (6)$$

where σ_{V_X}, σ_{V_Y} and σ_{V_Z} are the standard deviations of the three velocity components along the adopted reference frame.

4.2 Vorticity

The adoption of a Cartesian measurement grid allows the calculation of the vorticity component along the axial direction.

$$\omega_x = \frac{\partial \overline{V_z}}{\partial y} - \frac{\partial \overline{V_y}}{\partial z} \qquad (7)$$

4.3 Harmonic Analysis

Harmonic analysis on the wake data can be applied after interpolating the data onto a polar reference frame and calculating the tangential and radial velocity components. Typically the Fourier coefficients shall be provided up to the 12th harmonics of the axial, tangential, and radial velocity along azimuthal profiles at different radial positions (typically from r/R=.2 to 1.0 step 0.1).

4.4 Uses of the second order statistics

The second order statistic is very useful in diagnosing possible problems of the inflow to the propeller. For example it is possible to localize ship boundary layer or brackets and shaft wake impinging on the propeller disk better than using mean flow information.

For example, high values of the turbulence in the bracket wake or very large wake can point

out possible non-optimal bracket alignment (Figure 5). In the region of the attachment of the bracket to the shaft high values of the turbulence intensity can reveal possible flow detachment.

High values of turbulence intensity and vorticity can diagnose possible risk of cavitation in an early stage.
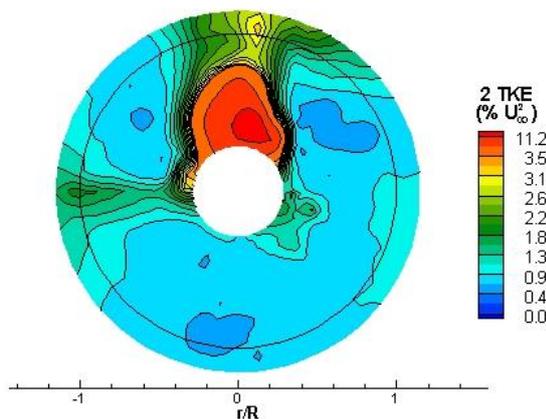

Figure 5: distribution of the turbulent kinetic energy in the propeller disk

5. UNCERTAINTY ANALYSIS

The evaluation of the uncertainty of a LDV measurement is a complex task due to the many factors involved and the complexity of the measurement technique. In the following, some considerations are provided as a general guide.

In general, error sources can be classified into three different classes: instrumentation accuracy errors, positioning errors and post processing errors.

Instrumentation accuracy errors: Errors due to the adopted optical configuration (measurement volume characteristics), are estimated to be around 1% of the measured velocity. Only in very special cases, when the angle between the laser beams becomes small the error will be larger. Error due to the velocity bias can be corrected by using volume transit time weighting as reported in § 3.1.

Positioning errors: This error is normally the largest in this type of measurement. A LDV probe is moved along the measurement grid by a traversing system with a given displacement accuracy. Furthermore, a positioning error is made, during the LDV probe alignment, which sets the origin of the coordinate system. This error is on the order of the target hole. Hydrodynamic loading on model and probe strut will displace further the measurement volume from the desired measurement position introducing further errors that could be very large in regions of strong velocity gradients.

Processing errors: The evaluation of the mean flow characteristics at a point is performed over a data population that could differ from point to point depending on both the fluid dynamic features and the local performance of the LDV system (depending on the seeding conditions, the presence of air bubbles or reflections, etc.) The uncertainty of the measurement can be performed by evaluating the confidence interval of the statistical estimators.

6. DATA PRESENTATION AND REPORTING

In the report the following information shall be provided:

- experimental setup (i.e. model setup, LDV system setup)
- measurement grids;
- table and contour plot of the measured velocity data with the value of data population at each measurement point;
- table and contour plot of the tangential and radial velocity in a polar reference frame;

- table and contour plot of the turbulence intensity or turbulent kinetic energy;
- Wake Harmonic analysis, up to the 12th harmonic, at different radii from r/R =0.2 to 1.0 step 0.1