LDV phase sampling technique in the analysis of installed propeller wake

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LDV phase sampling technique is developed and adopted for the analysis of the flow upstream and behind a four blade, highly skewed installed propeller, for the case of a twin screw ship model in a large circulating water channel. The implemented technique allows the reconstruction of the 3D flow field for each revolution angle in transversal planes located as close as possible to the blade trailing and leading edge. The main features of the propeller installation are highlighted as well as the strong and complex interaction of the propeller with the hull wake, especially in the brackets region.

INTRODUCTION

The accurate analysis and knowledge of the propeller flow field in non uniform inflow has a fundamental role in the naval field where propeller feels the effect of the upstream wake. Non uniform incoming flow induces radial and angular variable working conditions along the blade span and hence thrust and torque distribution that changes during the revolution; this could produce propeller-induced vessel vibration, unsteady cavitation and noise generation. In such situations it is desirable to have a detailed description of the flow field distribution around the propeller, to be used for both new design approach as well as for analysing propulsive, hydro-acoustic and structural performances, induced by propeller-vessel coupling. Furthermore, the experimental investigation provides baselines to improve and integrate theoretical forecast and to develop and validate numerical codes.

The development of laser Doppler velocimetry (LDV) allows suitable experimental investigation of complex fluid dynamic fields, like propeller wake, where strong vortex structures, turbulent fluctuations, three-dimensional boundary layer, marked velocity gradient occur (Min. K.S. 1978, Kobayashi 1982, Hoshino & Oshima 1987).

Many works studying the behaviour of a propeller in uniform inflow are available in literature. In fact the 3D flow field in a transversal plane behind a propeller can be easily reconstructed by sweeping the measurement volume of a three components velocimetry system along a radius (Chesnakas and Jessup 1998) or along two orthogonal radial directions of a two components velocimetry system (Cenedese et al. 1985, Lammers 1988, Jessup 1989, Stella et al. 1998). Hyun and Patel (1991) by using the same procedure and hot wire anemometry extended the study of the propeller flow to the case non uniform inflow but still in the hypothesis of axisymmetry flow (propeller installed in the wake of a axisymmetry body).

More complex is the case of a real propeller installation. In such case the axisymmetry hypothesis is no more valid and the experimental investigation of the propeller wake requires a complete sufficiently dense grid in the investigation plane, for a given propeller angle, in order to resolve the flow structures during the propeller revolution. Therefore, phase sampling techniques developed for the empirical analysis of 3D propeller wake in a uniform incoming flow, require to be extended to the all investigation plane and no more only to one or two radius. For such reasons the experimental analysis is particularly onerous, requires several days of facility occupancy and very performing computational and data storage resources. For those reasons there is a lack of available data in literature regarding flow field survey around installed propellers.

The LDV measurements presented in this paper were carried out at the INSEAN Circulating Water Channel, for the case of a four blade twin-propeller ship model.

Measurements show the behaviour of the average and turbulent velocity field at different angular propeller positions, pointing out the interaction between hull wake and propeller blades, especially in the brackets area.

Due to the lack of space in the present paper and to the large amount of data obtained in the measurement campaigns, only few results can be presented.

Although wake details are strictly dependent on both the geometry of propeller, the inflow characteristics and the loading conditions, results of this investigation will be

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discussed with emphasis on those flow features and processes of a general content.

EXPERIMENTAL SET UP

Experimental facilities

Measurements were carried out at the INSEAN Circulating Water Channel, a free surface channel with 10m length, 3.6m wide and 2.25m depth test section that allows 5.2 m/s water flow maximum speed with controllable reference pressure till 40mbar. The four blades, adjustable-pitch, highly skewed propeller model has been built in 1:20 scale ratio: D_e=275mm, pitch-diameter ratio P/D_{07}=1.636, expanded area-disk area ratio A_e/A_0=0.703. The ship-model is a dummy model of about 6.4 m length with the stern in geometrical similarity (1:20 scale ratio from transom to the 8/20 midship section station) and contracted bow shape with the same original areas distribution, having the main goal to reproduce the same inflow condition at the propeller disc as in the real ship. A sketch of the experimental set-up is shown in figure 1. A 5W argon laser, differential, two channels, backscatter LDV system was used. The frequency shift, required for the velocity versus recognition, was provided by a 40MHz Bragg cell. The three dimensional velocity field measurements were performed in two separate steps by means of two different optical configurations, measuring respectively the components on a vertical plane parallel (V_x, V_z) and perpendicular (V_y, V_z) to the rotating shaft. A rotary 3600 pulse/revolution encoder supplied the actual propeller position with an angular resolution of 0.2°. The encoder signals were processed by a synchroniser which provided the propeller angular position to a two-bytes digital port available on the LDV master processor. The measurement volume displacements on the test section were carried out by moving the underwater LDV probe mounted on a three degree of freedom traversing system. In order to improve the Doppler signal processor data rate and to reduce the acquisition time at point, the tunnel water was seeded with Titanium dioxide (TiO_2) particles, provided up stream the ship model by using a special seeding rake device. Data acquisition was accomplished by using a PC while post processing analysis was performed on a workstation with high data storage capabilities (15 Gbyte)

Measurement Grid and Test Condition

Tests were carried out at the propeller angular velocity of 7.7 rps with the tunnel water velocity of 2.4 m/s, corresponding to an advance ratio equal to 1.10 and a blade Reynolds number at 0.7 r/R equal to $3.7 \cdot 10^5$. Measurements were performed on two planes located upstream (x/R=-0.49) and downstream the propeller (x/R=0.742). The measurement grid choice was defined looking at the spatial resolution, which must resolve the propeller wake structures and to correctly describe the velocity field in the brackets area, where the highest velocity gradients are expected, as well as minimising the number of points in order to reduce the time required for the test. For this purpose a z and y uniform Cartesian map, thickened in the brackets area, was used. The measurement disk radius R_m was 158.125 mm, slightly bigger then the propeller radius (R_e=137.5 mm) to resolve the blade tip structures, possible ship boundary layer trace and wake variations along the diameter.

To cover the complete disk area of the propeller, grid of about 400 points ($\Delta y = \Delta z \cong 12$mm) has been adopted, referred to a Cartesian system with the origin in the centre of disk propeller, X axes coincident with the shaft axes, fore-aft oriented, Y axes horizontal, starboard oriented and Z axes vertical, up oriented.

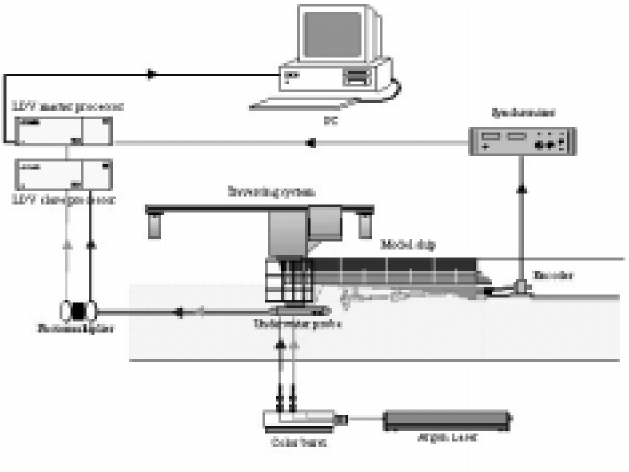

Figure 1: sketch of the experimental set up

Phase sampling technique in non uniform inflow

In non uniform inflow condition, typical of installed propeller, the flow field is unsteady and periodic also in a propeller blade reference frame. Therefore, phase sampling techniques developed for the analysis of a propeller wake in a uniform inflow, that can be easily conducted by only radial movements of the measurement volume, are inadequate. In such conditions, instead, the measurements require a sufficiently dense map, whole measurement disk wide, for each different propeller angle. The statistical analysis must be performed by means of phase sampling procedure in order to obtain an ensemble averaging. The average is made by a large number of complete propeller revolutions.

The TTT (Tracking Triggering Technique) phase sampling technique (Stella et al 1998) was adopted in the analysis of propeller wake flow, allowing data acquisition process to be very fast and efficient since data quantity to memorise is automatically minimised. The velocity sample is acquired when Doppler signal is detected on the corresponding LDV system channel. This process is repeated independently in the two LDV channels because it is experienced that Doppler burst detection is not necessary simultaneous. Any LDV sample is tagged with the angular propeller position at the measurement time, provided by the encoder-synchroniser system, and then arranged inside N angular slots, 2ε wide (*slotting technique*).

Statistics is performed inside each slot to obtain mean flow field and turbulence intensity information.

The slotting parameter choice is critical for this kind of analysis as described by Stella et all (2000). In fact a compromise should be obtained between the need to increase the angular resolution, required to capture the velocity fluctuations (smaller slots), and to have an adequate number of samples inside the slot for the consistency of the statistical estimators (larger slots)

For such reasons, the standard slotting procedure (N contiguous slots, 2ε wide, from 0° to 360°) proves too much disadvantageous for the statistical processing accuracy. Therefore, more complex slotting procedures were implemented in order to obtain an optimal compromise between statistical requirements and angular resolution, in critical data rate conditions too.

Three independent slotting procedures were developed for the post-processing phase: *overlapping*, *blade slotting*, *weighted slotting.*

The *overlapping* procedure provides partial overlapping, Δε wide, for contiguous slots. Therefore, any sample in the overlapping area increases the statistical population in the two overlapped slots simultaneously, with statistical processing benefit.

The *blade slotting* procedure is based on the hypothesis of considering the propeller blades identical both in mechanical and geometrical terms. With this hypothesis, the velocity field at the measurement point, for the angular position $\theta(t^*)$, recurs periodically N_{blade} times during the propeller revolution (figure 2). Then, the slotting procedure can be limited inside an angular sector $2\pi/N_{blade}$ wide: a certain slot with centre θ_i and 2ε wide, will contain each velocity sample acquired when the angular position is $\theta(t^*) + 2\pi n/N_{blade}$ $(n=0,1,\ldots N_{rev}-1)$, with $\theta(t^*)$ such to respect the following belonging condition (figure 3):

$$\theta_i - \varepsilon \le \theta(t^*) \le \theta_i + \varepsilon$$

In each slot, the blade slotting procedure increases the samples population of a factor corresponding to the propeller blades number.

In the *weighted slotting* procedure a weighted average is introduced in the statistical analysis so that the influence of each sample will progressively decrease with fixed law (linear, Gaussian) as its distance from the slotting centre, with accuracy improvement.

In the following the result were obtained using blade slotting technique with 90 overlapped slots of 2ε=2° amplitude and weighted average with Gaussian law.

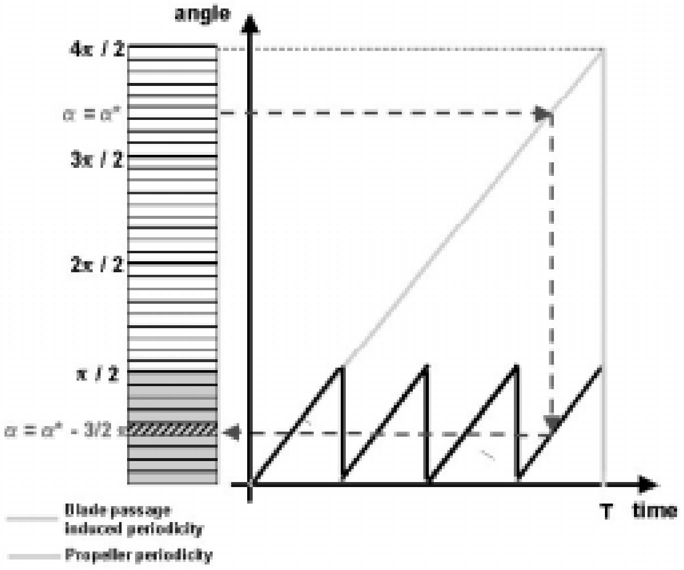

Figure 2: blades induced periodicity

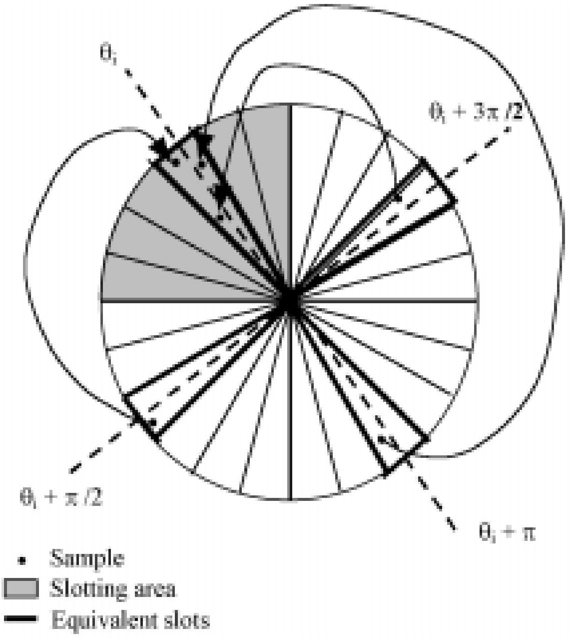

Figure 3: blade slotting procedure

This choice represented an optimal compromise, allowing a statistical population of about 150÷200 samples per slots (obtained with 180 seconds of time acquisition at a point and a data rate of about 200 samples per second), and an angular resolution able to accurately resolve the high velocity gradients too.

WAKE ANALYSIS

In figure 4 the wake generated by the hull without the propeller installed is reported (nominal wake measured at x/R=0) in order to have, in the following discussion, a better understanding of the inflow condition.

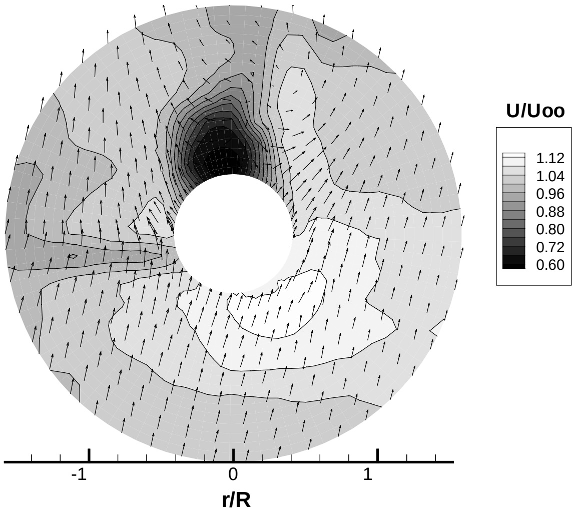

Figure 4: nominal wake. 3D wake non dimensional by the free stream velocity

The velocity distribution shows a typical behaviour for twin screw ships with “L” bracket configuration and the following characteristics are pointed out:

- The propeller is installed in a region where mainly only the potential effect of the hull is important even if ship boundary layer can influence the outer regions of the propeller disc, near the ship wall. For this reason, the wake coefficient (U/U_∞) is around .95 which is a typical value for twin screw ship
- The wakes of the brackets and of the shaft are well apparent in the axial velocity as well as in the turbulence levels distribution (figure 5). A separated region in the junction of the vertical brackets with shaft can be noticed
- The effect of the brackets is important because a strong deformation on the wake is induced, due to the fact that they act as wings at incidence

Two planes where considered for studying the propeller flow field: an upstream plane at x/R=-0.49 and a downstream plane at x/R =0.742. They were selected as the closest to the propeller disc, allowing optical access to the whole measurement plane. Wake evolution is described by the representation of the velocity field during the revolution period; so, each velocity distribution, in the measurement plane, is related to the corresponding blade angular position between 0° e 90°, (blade slotting procedure):

$$\vec{V}(x,y,z) = F(\theta(t))$$

where $\theta(t)$ is the propeller angular position. In the following, for space reasons, just three representative angular positions of the inward rotating propeller can be shown. In the following, plots show the flow field of the right propeller, rotating in counter clock wise direction, seen from a downstream view point.

In figure 6 the axial velocity distribution in the upstream measurement plane, for the blade angles 30°, 60°, 90° is shown.. The main characteristics of the nominal wake are recognised in the iso-countour. Furthermore, the effect of the propeller suction is apparent. The velocity defect of the shaft and of the vertical bracket as well as of the horizontal one are not removed. The propeller effect, on the upstream plane, can be considered potential and the resultant flow field to be the superposition of the nominal wake and the propeller induced velocities.

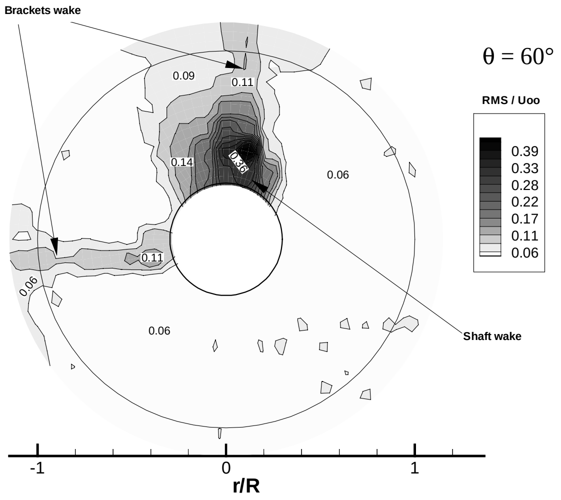

Figure 5: upstream wake. Turbulent Intensity of the axial component non dimensional by the free stream velocity

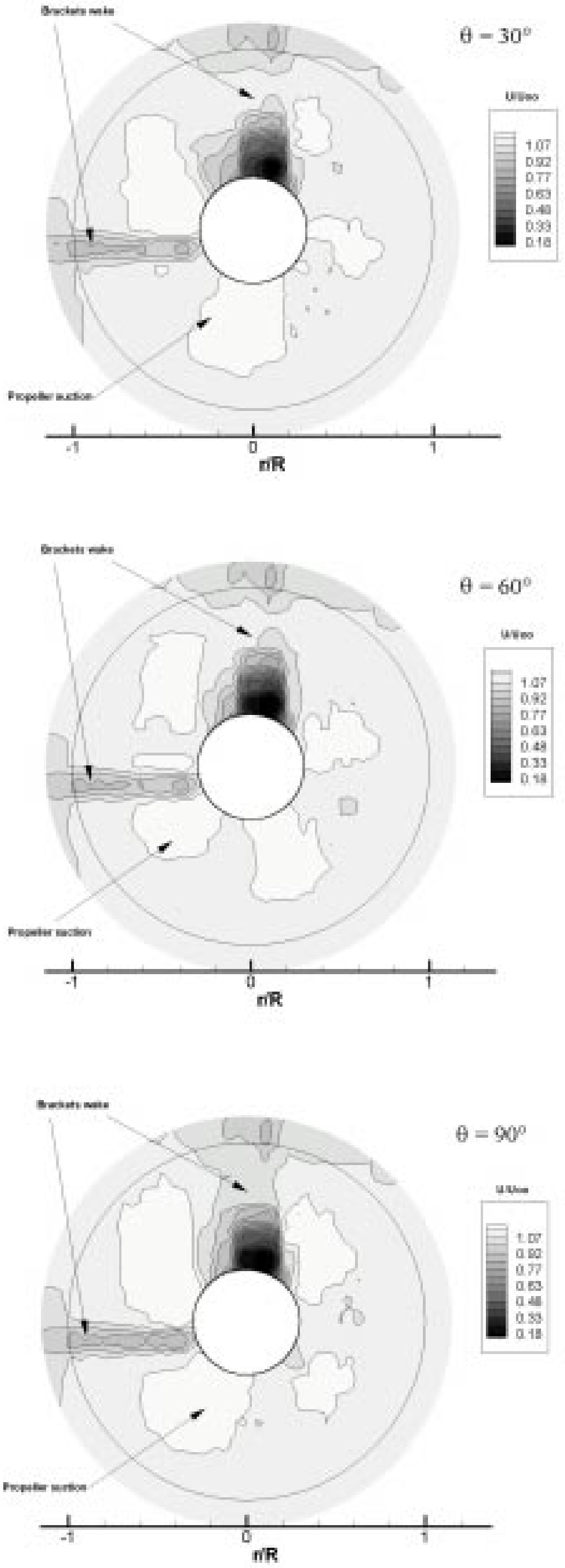

Figure 6: upstream wake. Axial velocity field non dimensional by the free stream velocity at θ=30°, 60°, 90°

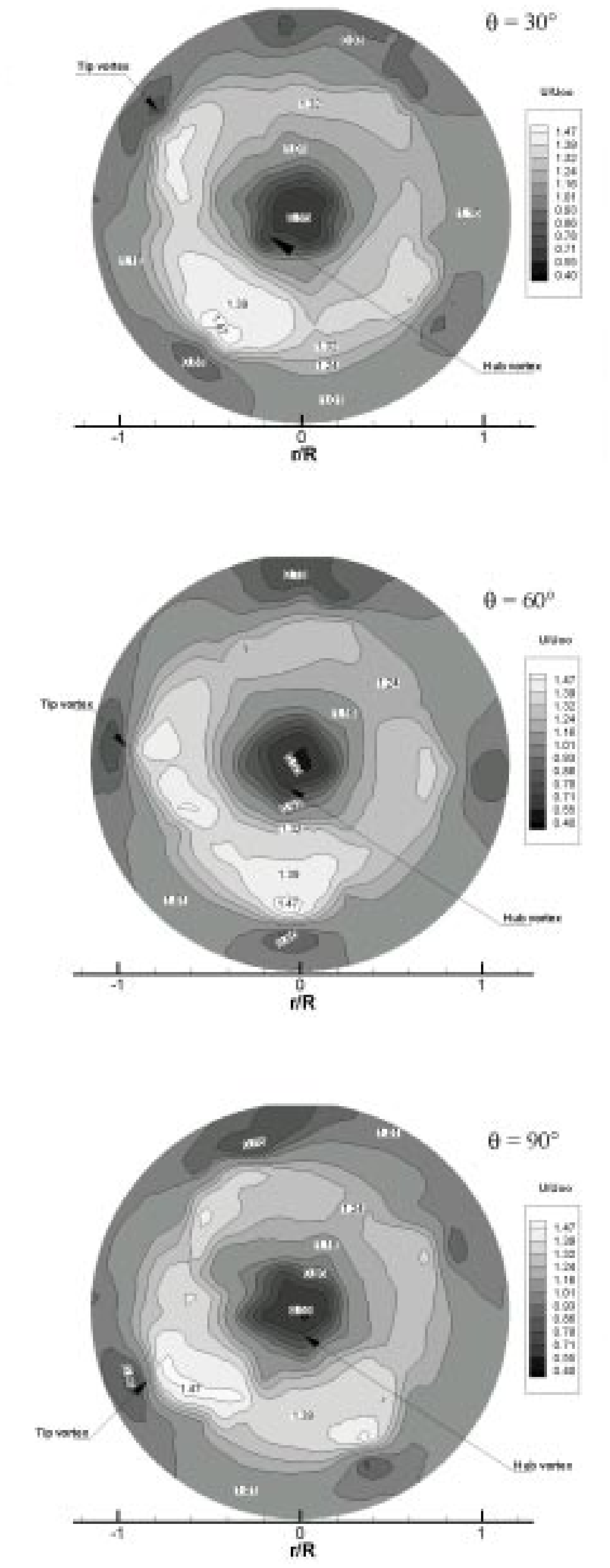

Figure 7: downstream wake. Axial velocity field non dimensional by the free stream velocity at θ=30°, 60°, 90°

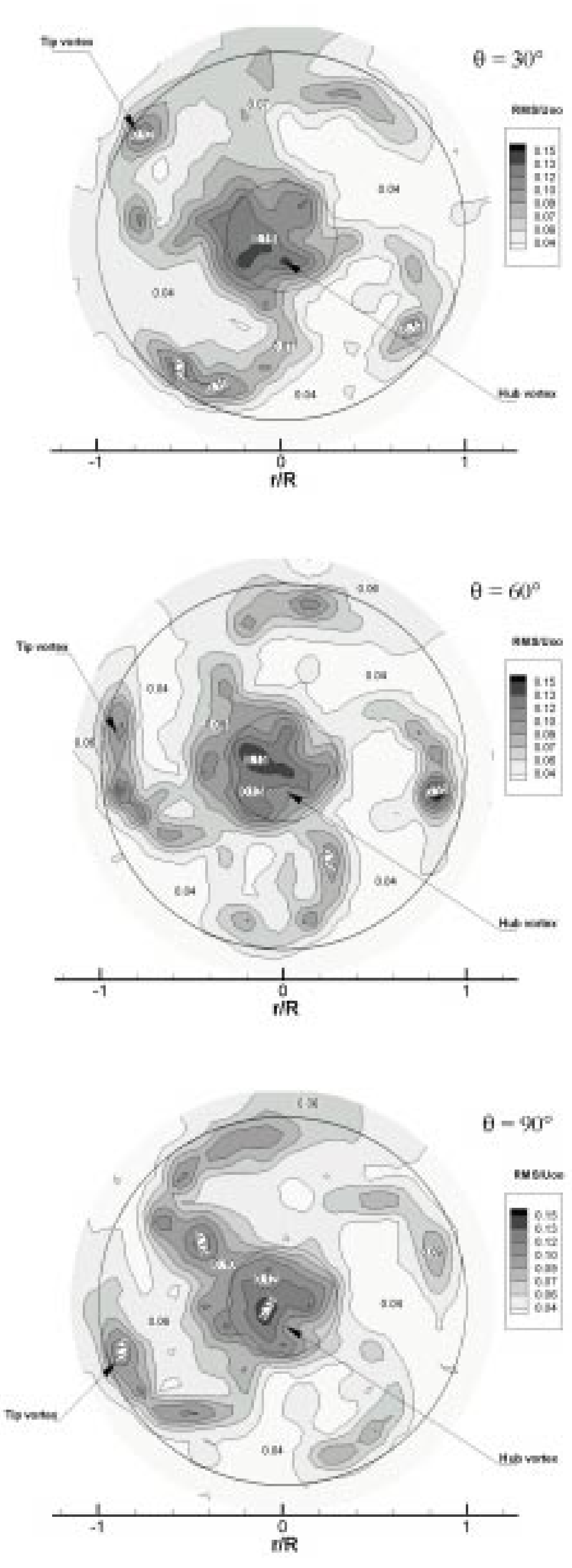

Figure 8: downstream wake. Axial component turbulence intensity non dimensional by the free stream velocity at θ=30°, 60°, 90°

In figure 7 the axial velocity field downstream the propeller, at the blade angles = 30°, 60° and 90° is shown.

The effect of the four blades in the wake is recognisable and velocity distribution is not axisymmetric because the propeller is working in a non uniform inflow, generated by hull wake. Especially in the brackets shadow, there is a strong increasing of the blade angle of attack and, consequently, higher velocity peaks. A phase shift between these peaks and brackets position is due to the convective effect in the wake, which is rotating with the propeller. In the figures, the trace of a tip vortex and hub vortex are indicated by the arrows. Tip vortices appear inside the propeller disc trace due to the contraction of the propeller streamtube.

The velocity defects in the wake of the blades, due to the boundary layer and shown in many isolated propeller wake measurement, are not well visible in the measurement plane because the process of diffusion and dissipation already took place before x/R= 0.742, fading and smoothing most of the gradients.

The downstream velocity distribution at x/R= 0.742 doesn't contain, in the mean axial component, any information which resembles the upstream plane, pointing out the capability of the propeller, highly skewed, to compensate and mediate upstream flow non uniformity.

This is not true for the second order statistic. In fact the turbulence levels of the axial velocity component (ratio between rms and the upstream velocity), shown in figure 8, point out that trace of the shaft and vertical bracket wake are still present in the downstream plane. The turbulence levels show the location of the blade wake in the measurement plane, pointing out also the wake deformation due to the tip and hub vortex action.

In the tip vortex core high turbulence levels are observed, especially in the brackets area where, due to the action of brackets and shaft wake, the tip vortex is shaken.

The interaction between blade turbulence and shaft wake induces diffusion of the turbulence in a large region in the upper part of the measurement disc. The convective effect, due to the velocity induced by the propeller, rotates this zone in the sense of rotation of the propeller.

From the designer point of view, turbulence levels provide interesting information on the propeller working conditions and give an evaluation of the efficiency better then the averaged velocity field; in fact turbulence subtracts energy to the flow and than to the thrust. Furthermore, flow regions where turbulence levels achieve highest levels can be considered as noise sources and cavitation inception points.

To complete the description of the velocity field in the propeller wake, in figure 9, the cross-flow in the downstream plane is shown for the angles θ= 30°, 60° and 90°. In such figures the tip vortex trace in the plane, having almost elliptical shape, is recognised. Furthermore the wake flow is dominated by the strong circulation generated by the hub vortex which is swirling the flow.

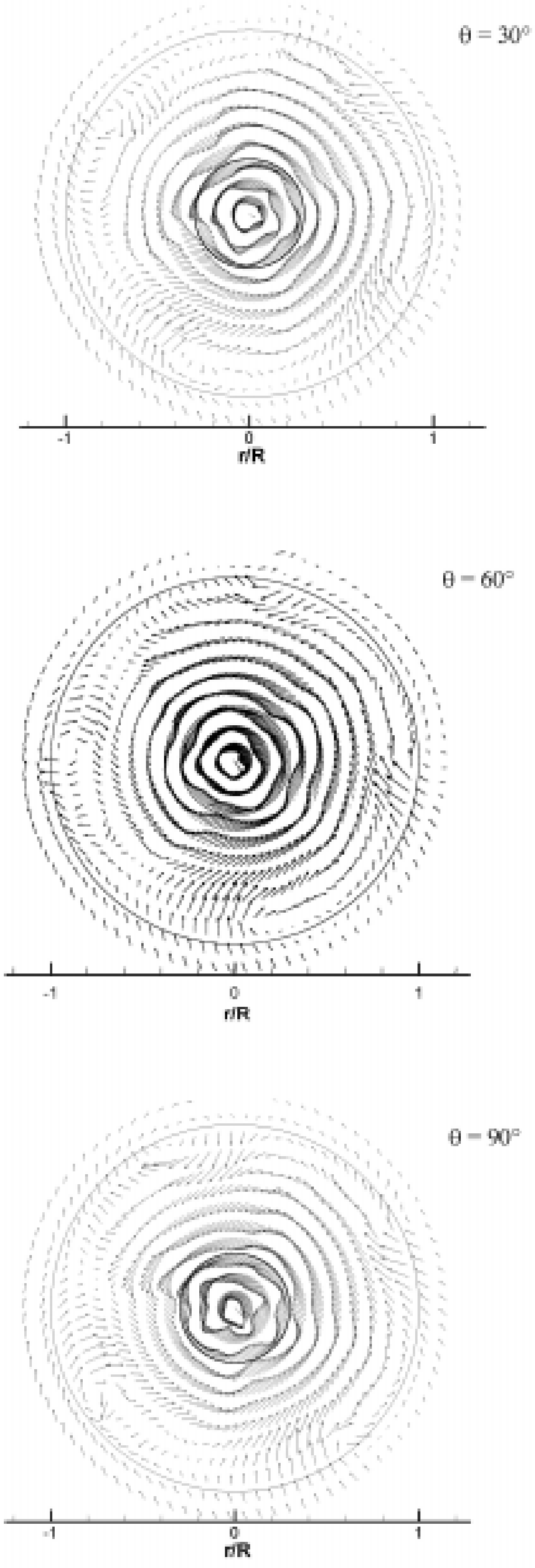

Figure 9: downstream wake. Crossflow field at θ=30°, 60°, 90°

The same information is pointed out by the vorticity map, shown in figure 10. In such figure also the vorticity released by the blade as well as by the tip vortex can be noticed. The vorticity released by the blade changes the sign approximately at r/R =0.65 suggesting that this the blade section where the maximum circulation and load are achieved. Furthermore, figure 10 shows the complex structure of the hub vortex and the presence of secondary vortices near the tip due probably to the modulation of the circulation on the blade caused by the variable loading condition of the propeller during the revolution.

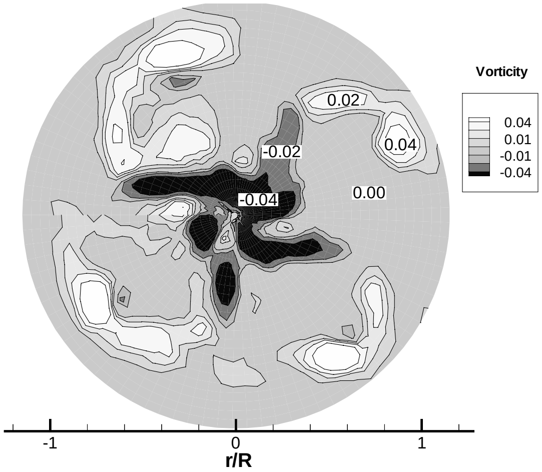

Figure 10: downstream wake. Vorticity field

CONCLUSIONS

The adopted LDV phase sampling technique allows an effective reconstruction of an installed propeller wake.

Phase sampling was performed by means of Tracking Trigger Techniques, arranging the velocity samples inside angular slots, dependently from the propeller position at the measurement time (slotting technique). Special slotting techniques were developed in order to increase the statistical population and to reach an optimal compromise between statistical requirements and angular resolution: this provides a better quality of the measurement, limiting the time required for the data acquisition.

The experimental results have pointed out significant features of the flow field around the installed propeller:

- The propeller effect, on the upstream plane, can be considered potential and the resultant flow field to be the superposition of the nominal wake and the propeller induced velocities;
- The propeller wake loses its axisymmetric morphology, typical of the propeller wake in uniform inflow, however the corresponding thrust centre displacement towards the ship centre line (for the

adopted propeller revolution configuration) is very small;

- In the downstream plane, information resembling the upstream flow can be found only in the second order statistics;
- The brackets and shaft turbulent wake destabilises the propeller tip vortex system; this is highlighted by the increased turbulence levels of the tip vortex core when crossing this regions;
- The high resolution obtained allows a detailed description of the vorticity released at the blade tip and leading edge where secondary vortices were found, due probably to the variable loading condition of the blade during the revolution.

AKNOWLEGMENTS

The present work was supported by the *Ministero dei Trasporti e della Navigazione* in the frame of the INSEAN Research Program 1996-99.

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