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# Analysis of the Propeller-hull Interaction by LDV Phase Sampling Techniques

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*Abstract* : In the present paper the results of the wake survey in two stern sections of a twin screw ship model, located just upstream the propeller disk and behind the directional rudder, are presented. Experiments have been performed in a large towing tank by using a Laser Doppler Velocimeter and phase sampling techniques, in order to analyse wake evolution with the propeller angular position. 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 and downstream the directional rudder.

*Keywords* : LDV, Propeller, Wake, Rudder

## 1. Introduction

In the last years, the accurate analysis of the velocity field induced by a marine propeller has been in need not only with the increasing power and speed of the ship but, especially, with the increasing demand for the more comfortable vessel. With the present emphasis on increased ship speeds and consequently much higher propeller thrust, in fact, hydrodynamic-induced noise and vibrations has became a very important problem both in navy and civil naval architecture. Vibratory forces, which are predominantly applied at blade frequency, have frequently caused local structural failure by producing fatigue and, in many cases, have precluded the occupancy of parts of passengers vessels because of the noise and discomfort attending the resonance of decks and bulkheads.

The problem of reducing propeller induced noise and vibrations leads to an increased complexity of blade geometry, primarily due to the low aspect ratio and to the skew, and has implied a rising interest on detailed measurements of the propeller flow field, to be used for both new design approaches as well as for analysing propulsive, hydro-acoustic and structural performances.

On the other hand, the experimental investigation provides baselines to improve and integrate theoretical predictions and to support the flow modeling and the validation of computational codes (BEM, RANS, LES). In these last years, the development of velocity measurements in phase with the propeller, based on the adoption of non intrusive velocimetry techniques (LDV, PIV), has been a turning point in the analysis of the complex flow field in the propeller region, characterized by the occurrence of strong vortex structures, turbulent fluctuations, three dimensional boundary layer and marked gradients (Kobayashi, 1982, Jessup, 1989, Stella et al., 2000, Di Felice et al., 2000).

In the present study the results of LDV measurement campaign, carried out at the INSEAN towing tank, along two transversal sections, located just upstream the propeller disk and downstream the ship rudder of a twin screw propeller ship model, will be presented and discussed.

Problems due to the considerable facility size (experimental set up rigging, requirement to assure an efficient seeding of the towing tank water) and its employment specifications (like the exigency of planning sufficient pause between two consecutive towing carriage runnings in order to assure ship model induced waves reduction), as well as the amount of the whole measurement campaign, rendered the acquisition and post processing phases particularly onerous and complex. Measurements regard a phase analysis (Felli et al., 2000, Stella et al., 2000) of the average and turbulent velocity field with the propeller angular position.

This allows to better describe the interaction between the propeller and the ship model, especially downstream the rudder and the shaft brackets.

# 2. Experimental Set Up and Test Condition

## *2.1 LDV Experimental Set Up*

Measurement campaign has been carried out at the INSEAN towing tank, a facility of 476 m length, 13.5 m wide and 6.5 m depth, for the case of a twin screw ship model of 6.4 m length, in $\lambda$=20 scale ratio. The four blades propeller was a stock model built with the following features: De=210mm, pitch-diameter ratio $P/D_{0.7}$=1.234, expanded area-disk area ratio Ae/A0=0.745. Ship model has been fixed on a towing carriage whose velocity fluctuations are circumscribed inside a range 1.5 mm/s wide around the test velocity. Flow velocity components have been measured by means of a two components back scatter LDV system, in which a 6W argon laser produces a radiation collimated by an underwater fiber optic probe and focalised in the measurement point by a 465 mm focusing lens. With the adopted optics, the measurement volume axes were 0.2 mm, 0.2 mm and 4 mm. The three dimensional velocity field measurements have been performed in two separate steps by means of two different optical configurations with the laser beams coming from below and one side, in order to measure the axial-transversal and axial-vertical velocity components respectively. The propeller angular position, measured from a rotary incremental encoder with a resolution of 0.1° and a synchronizer, has been provided to the LDV master processor by means of a two byte digital port and then transmitted to a PC together with the corresponding Doppler signal (Tracking Triggering Technique, Stella et al., 2000). The measurement volume displacements have been performed by mounting the underwater probe on a three directional traversing system with an accuracy of 0.01 mm. In order to improve the Doppler signal processor data rate and to reduce the acquisition time at point, the tunnel water has been seeded with 1-μm Titanium dioxide ($TiO_2$) particles, provided downstream the ship model by using a special seeding rake device. Seeding has been systematically carried out at the beginning of each test day (because the particles density, very close to the water one, Titanium dioxide particles tends to float a long time before falling down, warranting a good seeding during the whole test day).

## *2.2 Measurement Grids and Test Conditions*

Tests have been carried out at the carriage speed of 1.035 m/s, with the propeller angular velocity of 3.75 rps, corresponding to an advance ratio J=1.31. Measurements have been performed along two transversal sections of the hull, located just upstream the propeller disk and along the vessel aft perpendicular, just downstream the rudder. The measurement grid choice has been defined looking at the spatial resolution, which must resolve the wake structures, especially in the nearby propeller sections, where highest velocity gradients are expected, as well as minimising the number of points in order to reduce the facility occupancy. At this purpose Cartesian maps of about 350 measurement points have been used. In particular, the aft perpendicular section measurement grid has been thickened along the rudder area in order to locally assure a bigger resolution of the wake structures.

In the upstream propeller section, due to the shaft occurrence, which restricts the LDV probe optical access, hull wake has been described by means of two grids in order to cover the whole measurement plane. In order to minimise the carriage runnings as well as to optimise the measurement points number acquired during each running, compatibly with the experimental "bonds" (propeller revolutions during the acquisition time at point, kind of analysis (phase or standard analysis)), acquisitions of 30 sec at point have been planned. In the present paper, velocity field is referred to a Cartesian system with the origin at the intersection between the aft perpendicular and the design water line in the plane of symmetry of the ship model, X axis longitudinal forward oriented, Y axis transversal starboard oriented and Z axis vertical, upward oriented.

## *2.3 Phase Sampling Techniques*

Phase analysis has been carried out by using the Tracking Triggering Technique (TTT) (Stella et al., 2000), allowing the acquisition process to be efficient and fast. Velocity samples are acquired when Doppler signal is detected in any of the two LDV channels and tagged with the reference blade angular position at the measurement time.

This process is repeated independently in the two LDV channels because it is experienced that Doppler burst detection is a random event and not necessary simultaneous.

In the post processing phase, data are ordered inside angular slots of constant width and statistical computation performed for each slot to obtain mean flow field and turbulence intensity information.

The slotting parameter choice is critical for such a kind of analysis. In fact a compromise should be adopted between the need of increasing the angular resolution, required to capture the velocity gradients (smaller slots), and of having 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, $2\varepsilon$ wide, from 0° to 360°) provides poor statistical processing accuracy. Hence, more complex slotting procedures, like overlapping, blade slotting, weighted slotting, have been implemented in order to obtain an optimal compromise between statistical requirements and angular resolution, in critical data rate conditions too (Felli et al., 2000).

In the present analysis, statistical evaluation has been performed by using blade slotting technique with 360 overlapped slots of amplitude $2\varepsilon=2°$ and weighted averaging by gaussian law. With this choise, meanly 150 ÷ 400 samples per slot, have been collected. In addition angular resolution is adequate to describe flow regions with high gradients.

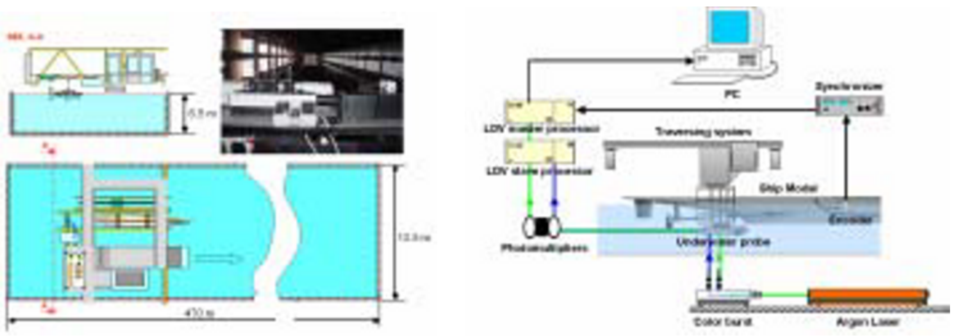



Fig. 1. Test facility (left) and experimental set up (right).

## *2.4 Uncertainly Analysis*

Error sources can be classified in three different classes: instrumental accuracy errors, positioning errors, post processing errors.

Instrumental accuracy errors: the INSEAN LDV system accuracy, in the adopted optical configuration, is estimated to be around 1%.

The accuracy with which a particle follows the fluid motion can be estimated by considering the velocity lag of a single spherical particle in a continously accelerating flow (Adrian, 1991). In the present case the velocity lag of a $TiO_2$ particle, calculated in the tip vortex and considering a mean acceleration $a = \omega^2 R_{tip} = 100g$ is of about 0.2 mm/s.

Positioning errors: LDV probe displacements have been carried out by the traversing system with an accuracy of 0.01 mm. A position error, within 0.5 mm, is committed in the LDV probe alignment on the target setting the origin of the co-ordinate system. The setting of the blade at the reference “zero” angular position, performed by using a strobe-light triggered by the synchronizer in order to align the blade with a plumb line, which crosses the propeller centre, is estimated to be within 2 degrees of accuracy.

Processing errors: the processing error is mainly due to the slotting technique during the statistical analysis of the acquired data. The averages inside each slot smooth the velocity gradients along the azimuth as a low-pass filter. This effect, however, has been found to be negligible for values of the slot width up to 2 deg (Stella et al., 2000). The adoption of a weighted slotting technique can improve the result, reducing this effect.

The uncertainty of the statistical analysis can be performed by evaluating the confidence interval of the statistical estimators.

Statistical population of the velocity samples changes in a wide range (100 ÷ 400) in dependence on the fluid dynamic features of the wake. The minimum values are achieved in the tip vortex due to the LDV signal processor drop out, because the strong velocity fluctuations. The uncertainty analysis, performed by using the t-Student distribution (for which the velocity uncertainly $\Delta v = \pm 1.96\sigma / (N-1)^{0.5}$ with a probability of 97.5%), gives results around 2 % and 1.5 % of the freestream velocity for the measurements in the tip vortex and in the blade wake, respectively.

# 3. Wake Analysis

Figure 2 shows the propeller influence on the upstream flow with the distance. The analysis has been performed by analysing blade induced periodicity distribution along eight longitudinal stations of the wake, from x/R = 0.44 to x/R = 0.96. Propeller induced suction, which causes a velocity peak during the blade passage, is relatively strong in the first station (x/R = 0.44) and decreases rather suddenly in the second (x/R = 0.52) and third (x/R = 0.6) station. From fourth station (x/R = 0.68) propeller influence can be considered negligible. Upstream plane has been 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):

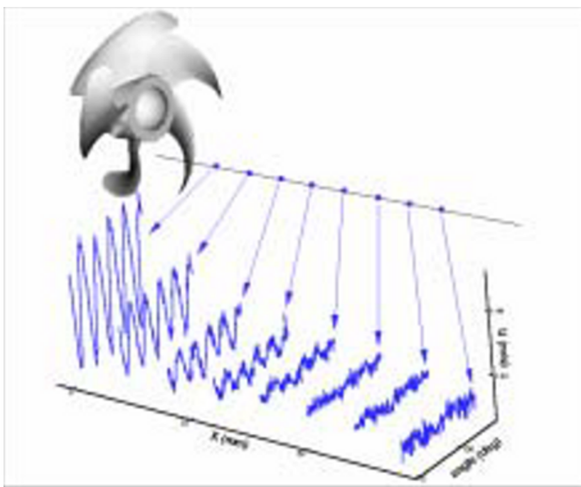


Fig. 2. Propeller influence on the upstream field.

$$\vec{V}(x, y, z) = F(\theta(t)) \tag{1}$$

where θ(t) is the propeller angular position. In the following, for space reasons, just only one representative angular position of the inward rotating propeller can be shown. Full animations can be downloaded from http://crm.insean.it. Phase analysis of an installed propeller wake, particularly onerous from an empirical point of view, because the axi-symmetry hypothesis is no more valid, gives important information in addition to the standard analysis, to be used for analysing propulsive, hydro-acoustic and structural performances induced by the propeller-vessel coupling (Di Felice et al., 2000, Felli et al., 2000).

In particular :

- the morphology and the angular evolution of the propeller suction effect on the inflow (Figure 3);
- the evolution of the tip vortices and their interaction with the hull wake, especially downstream the rudder (Figures 3 and 6);
- the downstream propeller wake evolution of the axial component, particularly useful for evaluating the centre of thrust displacement during the propeller revolution;
- the complex vorticity release at the blade trailing and leading edge where secondary vortices have been induced as a consequence of the blade variable loading conditions during the revolution (Helmotz theorem) (Figure 4).

Wake analysis allows to resolve the velocity defect induced by the shaft brackets (Figure 3). This effect can be explained as a consequence of both the viscous wake, originating in the boundary layer on the appendage surfaces, that is shed downstream from the brackets trailing edge, and the momentum transfer from the axial to the transversal components, typical of a lifting surface. The flow slow down, which appears in the upper side of the upstream plane (Figure 3), can be probably ascribed to the interaction with the hull counter.

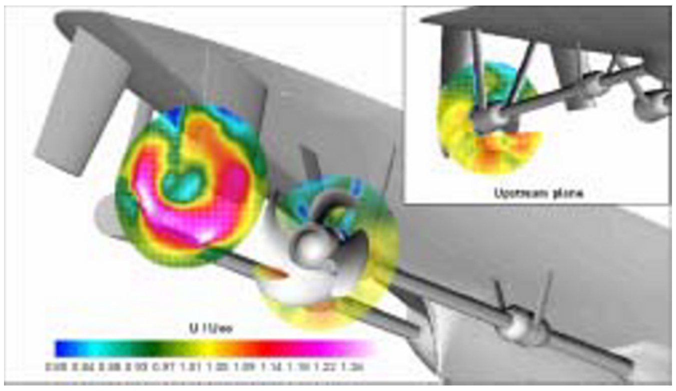


Fig. 3. Axial velocity field at the stern frames for $\theta$=40°.

Propeller suction appears as a lobe shape geometry which rotates with a progressive intensity increasing by moving in counter clock wise from the starboard to the midship half-plane (Figure 3: upstream plane). In the inner half-plane, in fact, the upstream wake, upward direct, is counter rotating with respect to the propeller and, hence, tends to locally increase the hydrodynamic incidence of the blade. This causes a centre of thrust displacement which can induce vibrations, noise and fatigue stresses on the rotating shaft. Therefore, in the downstream plane the axial velocity field loses the axi-symmetrical morphology, typical of an isolated propeller, with a maximum toward the symmetry plane where blade hydrodynamic loads are bigger than in the rest of the measurement plane.

The effect of the hydrodynamic load non uniformity is well apparent also in the streamlines trajectories characterised by a strong roll up in the toward symmetry plane side, due to the stronger intensity of the tip vortices (Figure 4), and by a weak outward displacement elsewhere.

Rudder occurrence causes a velocity defect of the wake well apparent in axial velocity iso-contours, with a thickness progressively increasing by moving upward.

This behaviour can be explained as a consequence of the not uniform distribution of the hydrodynamic load along the appendage span. In fact, in the upward sections ($r > 0.7R$), much far from the rotating shaft, the hydrodynamic incidence is bigger because the higher tangential velocity and the progressive decrease of the axial component (Figure 3). At purpose, figure 5 shows the distribution of the hydrodynamic load along the rudder span by considering the bound circulation distribution $\Gamma(s)$, calculated by integrating the vorticity field $\omega(s)$, as shown below:

$$\Gamma(s) = \int_A^B \omega(s)ds \tag{2}$$

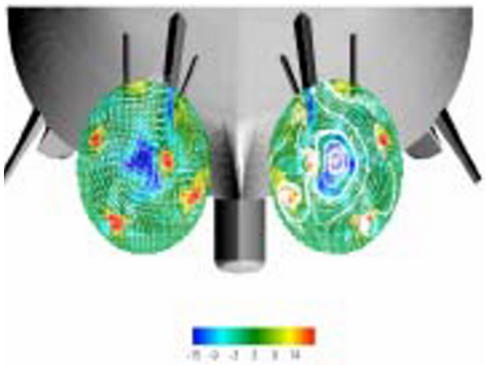


Fig. 4. Vorticity field with vectors (left) and streamlines (right) at the aft perpendicular for θ=30°.

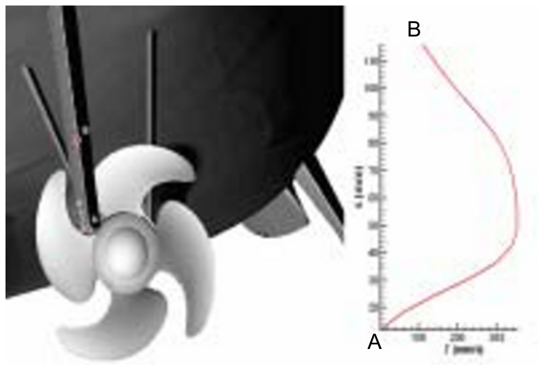



Fig. 5. Circulation distribution along the rudder span.

with the hypothesis of considering Γ(s1)=0, because circulation value at the appendage tip.

The analysis of the streamlines and the vorticity field points out the occurrence of two counter rotating vortices released from the rudder, fixed during the propeller revolution. Furthermore, figure 4 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 conditions of the propeller during the revolution.

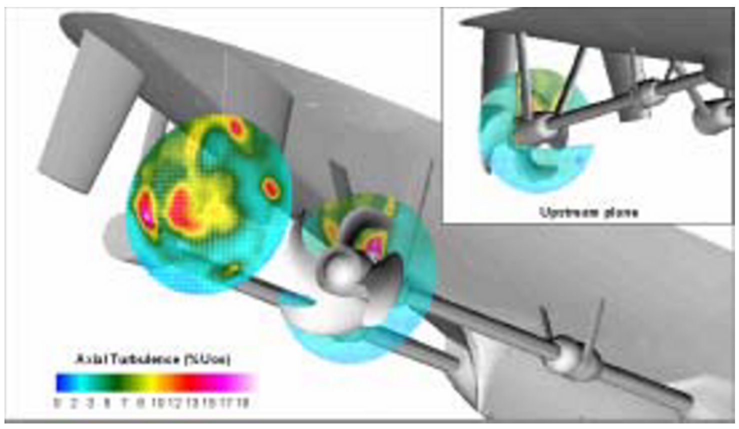
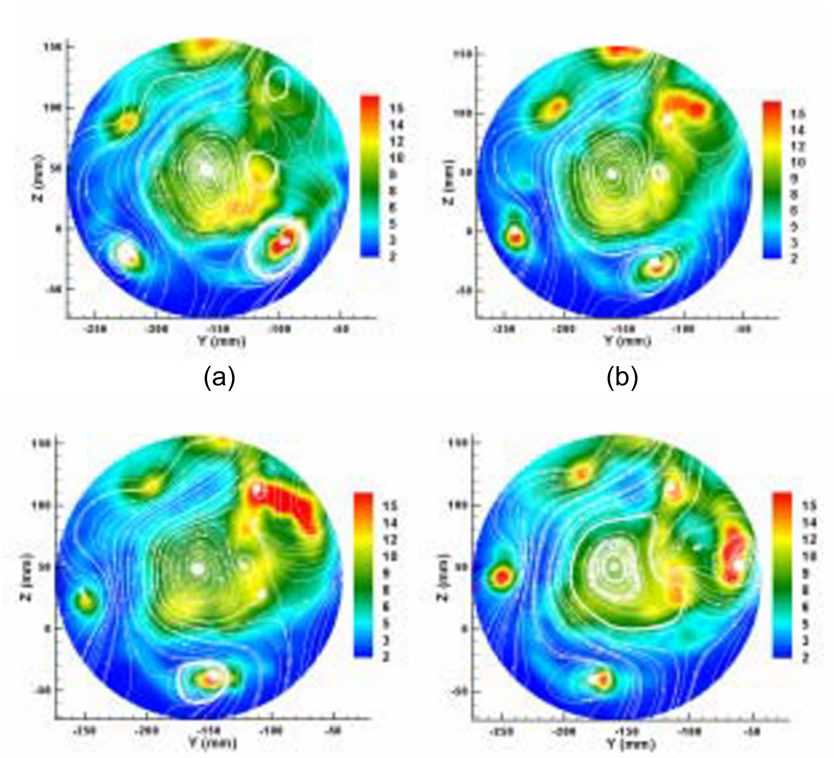


Fig. 6. Axial turbulence field at the stern frames for θ=30°.

The distribution of the axial component of the phase averaged fluctuating velocity $\sigma_x$ (indicative of the turbulent wake) for the angular position θ=60° is shown in figure 6. In the upstream plane the shaft brackets viscous wake, fixed during the propeller revolution, can be noticed, whereas the absence of any phase structure seems to confirm the potential nature of the propeller induced flow field (Esposito et al., 2000). The analysis of the turbulence levels in the downstream wake allows to resolve the trace of the rudder and the blades turbulent wake, pointing out the wake deformation due to the combined action of the tip and hub vortices.

Blade turbulent wake appears rather faded because the strong processes of turbulent diffusion of momentum and viscous dissipation of energy occours upstream the investigated region. In the tip vortex a different behaviour is instead observed, with a strong turbulent trace. These opposite characteristics can be explained considering the different nature of blade turbulence in comparison with that of the tip vortex. Being generated by boundary layer flow, the blade turbulent wake is composed by small-scale eddies, where the dissipation processes are effective. On the other hand, the highest turbulent energy content in the tip vortex is on the large-scale eddies. The downstream increase of the turbulence levels as well as the enlargment of the tip vortex core can be explained as an effect of the strong mean velocity gradients, the spiraling of the blade boundary layer in the roll-up process and the unsteady spatial oscillation of the slipstream. The blade tip vortex crossing along the rudder area is quantitatively described in Figure 7. Close to the rudder surface blade tip vortex is progressively slowed down and starts to deform itself while rolls up around the appendage (Figure 7 (a)). Suddenly, vortex trace appears very stretched on the other surface of the rudder where is strongly shaken because the interaction with the rudder tip vortex (Figures 7 (b) and (c)).



(a) (b)

(c) (d)

Fig. 7. Axial turbulence field at the stern frames for θ=14° (a), θ=32° (b), θ=50° (c), θ=68° (d).

# 4. Conclusion

Phase analysis on the propeller wake interaction with the hull has been performed by means of a Laser Doppler anemometer. Measurements, performed in a large towing tank, have been carried out along two transversal planes in the stern of a twin screw ship model, located upstream the propeller disk and just behind the rudder.

The analysis points out significant features of the propeller hull interaction especially downstream the shaft brackets and the directional rudder, where tip vortex is strongly shaken and streched.

## *Acknowledgments*

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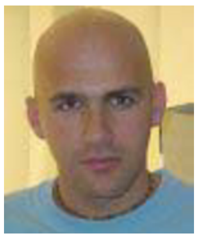
## *Authors Profile*



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