Analysis of the wake of a ship model with a single screw propeller by means of LDV

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Abstract

A phase sampling technique on random data acquired with LDV is developed to investigate the flow upstream and downstream a five blade installed propeller on a single screw ship model in a large circulating water channel. The technique allows the reconstruction of the 3D flow field for each angle of revolution along transverse planes located as close as possible to the blade trailing and leading edges. The main features of the propeller flow field are highlighted as well as the strong and complex interactions between the propeller itself and the hull wake.

1 Introduction

The accurate analysis and knowledge of the propeller flow field in a non uniform inflow has a fundamental role in the naval field due to the fact that the propeller just works inside the vessel wake. A non-uniform incoming flow induces working conditions which change along the radius and the azimuth and, hence, a variable thrust and torque distribution during the revolution. This could produce propeller-induced vessel vibrations, unsteady cavitation and noise generation. In such situations it is desirable to have a detailed description of the flow field around the propeller, to be used for approach to new design as well as
for analysing propulsive, hydro-acoustic and structural performances induced by the 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 the experimental investigation of complex fluid dynamic fields (as that in the propeller wake) where large vortical structures, high turbulent fluctuations, three-dimensional boundary layers and large velocity gradients occur (Min [12], Kobayashi [10], Hoshino [7]).

Many studies on the behaviour of a propeller in a uniform inflow are available in the literature. In this case, the 3D flow field in a transverse plane behind a propeller can be easily reconstructed by sweeping the measurement volume of a three component system along one radius (Chesnakas and Jessup [2]) or along two orthogonal radii for a two component system (Cenedese et al. [1], Lammers [11], Jessup [9], Stella et al. [14]). Hyun and Patel [8], by using the same procedure with hot wire anemometry, extended the study to the case of a non uniform inflow but still in the hypothesis of axial-symmetry (propeller in the wake of an axial-symmetric body).

More complex is the case of real propeller installations. In such a case, the previous hypothesis is no longer valid and the experimental investigation of the propeller wake during a revolution requires a 3D grid in the investigation plane, at each angle. Therefore, the phase sampling techniques developed for the analysis of the 3D propeller wake in a uniform inflow, must be extended to the whole plane and not only to one or two radii (Felli et al [5], Di Felice et al.[4]).

For such reasons, the experimental analysis is particularly heavy, requiring several days of facility occupancy and performing computational and data storage resources. This is why there is a lack of data in the literature regarding such a 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 five blade single propeller ship model. The measurements show the behaviour of the average and turbulent velocity fields at different angular positions of the propeller, pointing out the interaction between the hull wake and the propeller blades, especially in the skeg area. Although the wake details are strictly dependent on the geometry of the propeller, the inflow characteristics and the loading conditions, the results of this investigation will be discussed with emphasis on those flow features and processes of a general content.

2 Experimental set up

2.1 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.
which allows a 5.2 m/s water flow maximum speed with controllable reference pressure till 40 mbar. The five blades, adjustable-pitch, highly skewed propeller model has been built in 1:30 scale ratio: \( D_s = 188 \text{ mm} \), pitch-diameter ratio \( P/D_{07} = 1.03 \), expanded area-disk area ratio \( A_e/A_0 = 0.85 \). The ship-model is a tanker model of about 5.073 m length. 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. 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 (\( \text{TiO}_2 \)) 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 Gb).
2.2 Measurement Grid and Test Condition

Tests were carried out at the propeller angular velocity of 8.65 rps with the tunnel water velocity of 1.4 m/s, corresponding to an advance ratio equal to .5. The measurements were performed on two planes orthogonal to the shaft and located upstream and downstream the propeller disk respectively at about 0.3R and 0.7R. The measurement grid choice was defined looking at the spatial resolution, which must resolve the propeller wake structures and correctly describe the velocity field in the skeg 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 skeg area, was used. The measurement disk radius $R_m$ was 105mm, slightly bigger than the propeller radius ($R_c=94.20$ mm) to resolve the blade tip structures, possible ship boundary layer trace and wake variations along the diameter.

To cover the whole propeller disk, a grid of about 300 points ($\Delta y=\Delta z=10$mm) has been adopted, referred to a Cartesian system with the origin in the centre of disk propeller, the X axis coincident with the shaft axes, fore-aft oriented, the Y axis horizontal, starboard oriented and the Z axis vertical, up oriented. The number of measurement points in the upstream wake was reduced at about 180 due to the effect of the skeg shape which doesn’t allow an easy optical access behind the hub.

3 Phase sampling technique in non uniform inflow

In non uniform inflow conditions, as for an installed propeller, the flow field is unsteady and periodic also in the propeller blade reference frame. In such a case, as previously reported, phase sampling techniques developed for the analysis of a propeller wake in a uniform inflow are inadequate. Instead, 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 propeller revolutions.

Here, the TTT (Tracking Triggering Technique) phase sampling technique (Stella et al.[14]) was adopted; it allows a fast and efficient data acquisition procedure since the amount of data to be stored is automatically minimised. The velocity sample is acquired every time a Doppler signal is detected on the corresponding LDV system channel. This process is repeated independently on the two channels because it is experienced that the Doppler burst detection is not strictly simultaneous. Any LDV sample is tagged with the angular propeller position at the acquisition time, which is provided by the encoder-synchroniser system, and then arranged inside N angular slots, $2\pi$ wide (slotting technique). Statistical analysis is performed inside each slot to obtain the mean and $rms$ flow fields.
The choice of the slotting parameter is critical for such an analysis as described by Stella et al. [14]. Indeed, a compromise should be obtained between the need for increasing angular resolution (leading to small slots), and for improving consistency of the statistical estimators which requires an adequate number of samples inside each slot (large slots).

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

In particular, three independent refinements of the slotting procedure were developed for the post-processing phase: overlapping, blade slotting, weighted slotting (Felli et al.[5]).

In the following, the result were obtained using the blade slotting technique with 72 overlapped slots of 2ε=2° amplitude and a weighted average with the Gaussian law.

This choice represents 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.

4 Wake analysis

4.1 Nominal wake

In figure 2, the wake generated by the hull without propeller is reported (nominal wake measured at x/R=0) in order to have, in the following discussion, a better understanding of the inflow condition.

The perturbation induced by the hull is mainly concentrated at the top of the propeller disk downstream the stern skeg. Due to the skeg shape, in fact, a flow separation occurs as confirmed by the velocity defect of the axial component and from the turbulent wake width (iso-contour in figure 2).

The analysis of the cross-flow velocity field (vectors in figure 2) shows two bilge vortices in the upper part of the measurement plane (due to the symmetry of the nominal wake for a single propeller ship), whose origin and intensity are probably due to the stern shape close to the propeller.

In comparison to the case of a twin screw ship model (Felli et al.[5], Di Felice et al.[4]), the effect of the hull perturbation on is much more important, as confirmed by the lower value of the wake coefficient ($U/U_\infty=0.58$) which is within the typical values of a single screw ship.

The turbulence levels (on the right in figure 2) are maximum around the hub area and in the wake of the stern skeg where the flow is less regular and significant unsteadiness are present.
4.2 Upstream and downstream effective wake

Two planes were considered for studying the propeller flow field: an upstream plane at $x/R=-0.3$ and a downstream plane at $x/R=0.7$. They were selected as the closest to the propeller disc, which allow an optical access to the whole measurement plane. A third measurement plane at about $x/R=0.8$ was also considered in order to analyse the downstream wake evolution. The wake evolution is described by the representation of the velocity field during the revolution period; so far, each velocity distribution, in the measurement plane, is related to the corresponding blade angular position between $0^\circ$ and $72^\circ$, (blade slotting procedure (Felli et al. [5])):

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

where $\theta(t)$ is the propeller angular position. In the following, only two representative angular positions will be shown; the plots show the flow field of the propeller, which rotates in clockwise direction, from a downstream viewpoint.

In figure 3, the axial velocity distributions in the upstream measurement plane, for the blade angles $0^\circ$, $60^\circ$ are given. The main characteristics of the nominal wake are recognised in the velocity contours. Furthermore, the effect of the propeller suction is apparent only in the lower part of the measurement disk as confirmed by the high velocity regions corresponding to the track of two successive blades, which rotate in phase with the propeller.
Figure 3: The effective wake; axial velocity field in the upstream wake for \( \theta = 0^\circ \) (a) and at \( \theta = 60^\circ \) (b). The arrows indicate the position of the tip vortices.

In figure 4 the axial velocity field downstream the propeller, at the blade angles 0° and 20°, is shown. Due to the hull perturbation on the inflow, the velocity field loses the axial symmetric morphology typical of the isolated propeller (compare with figure 2). On the right side of the measurement plane, the inflow (which is directed upward and hence is counter-rotating with respect to the propeller) produces a strong increasing of the blade hydrodynamic load which consequently displays high velocity peaks. This effect causes a displacement of the centre of thrust which induces vessel vibrations and noise.

In the figures, the trace of a tip vortex is indicated by the arrows. The tip vortices appear inside the propeller disk due to the downstream contraction of the propeller stream tube. As a matter of fact, the acceleration of the flow by the propeller increases the momentum flux; the mass conservation principle imposes a contraction of the fluid streamlines downstream of the propeller.

The velocity defects in the wake of the blades due to the boundary layer wake (which is shown in many isolated propeller wake measurement) are not well visible here because diffusion and dissipation took place already before \( x/R = 0.7 \), fading and smoothing most of the velocity gradients. Due to the strong reduction of the blade thrust deriving from the flow separation in the wake of the stern skeg, the axial velocity falls down to about 40% of the free stream value.

The axial turbulent intensity field in the downstream propeller plane (figure 5) allows to point out important features of the wake, like the location of the blade wake, its deformation due to the tip and hub vortex action as well as the roll up of the viscous wake in a spiralling process around the vortex core.
Figure 4: The effective wake; axial velocity field in the downstream wake for θ=0° (a) and at θ=20° (b). The arrows indicate the position of the tip vortices.

Figure 5: The effective wake; axial turbulent intensity field in the downstream wake for θ=0° (a) and at θ=50° (b).

In the tip vortex core high turbulence levels are observed, especially in the right side of the measurement plane, where the bigger hydrodynamic loads are achieved, and during the skeg wake crossing, where the tip vortex shaken occurs. Moreover, the interaction between turbulence from the blade and the skeg wake induces turbulence diffusion in a large region on the upper part of the measurement disk.

From the designer point of view, the turbulence levels provide interesting information on the propeller working conditions and give an evaluation of the efficiency better than the average velocity field; in fact turbulence subtracts...
turbulence levels achieve the highest values can be considered as noise sources and cavitation inception points.

5 Conclusions

The phase sampling technique of LDV data employed in this paper allows an effective reconstruction of the effective propeller wake. Phase sampling was performed by means of the Tracking Trigger Techniques, which re-arranges the velocity samples into angular slots, depending on the propeller position at the measurement time (slotting technique). Special refinement techniques were developed in order to increase the statistical population of each slot and to reach an optimal compromise between statistical accuracy and angular resolution. This allows to obtain a better quality of the data, limiting the time required for the acquisitions.

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

- on the upstream plane the propeller effect can be considered as potential (ideal flow) and the resulting flow field as the overlapping of the nominal wake and of the propeller induced velocities;
- the stern skeg shape induces a wide separation region which causes locally a strong reduction of the propeller thrust;
- due to the separated flow region, confirmed by flow visualisations, the blade induced velocities are visible only in the lower part of the upstream measurement plane;
- the propeller wake looses its axial-symmetry, which is typical of the propeller wake in a uniform inflow, and the corresponding thrust centre displacement is lower than 0.1R;
- the stern skeg turbulent wake destabilises the propeller tip vortex system; this is highlighted by the increased turbulence levels of the tip vortex core when crossing this region;

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References


