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Analysis of the propeller wake by pressure and velocity correlation

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Abstract

In the present study an experimental analysis of the velocity and pressure fields behind a marine propeller, in non cavitating regime is reported. Velocity measurements were performed in phase with the propeller angle by using 2D Particle Image Velocimetry (2D-PIV). Measurements were carried out arranging the light sheet along the mid longitudinal plane of the propeller, to investigate the evolution of the axial and the radial velocity components, from the blade trailing edge up to 2 diameters downstream. The pressure measurements were performed at four radial and eight longitudinal positions downstream the propeller model. Measurements of the pressure field were performed at different advance ratios of the propeller. Pressure data, processed by using slotting techniques, allowed to reconstruct the evolution of the pressure field in phase with the reference blade position. In addition, the correlation of the velocity and pressure signals was performed.
The analysis demonstrated that, within the near wake, the tip vortices passage is the most important contribution in generating the pressure field in the propeller flow. The incoming vortex breakdown process causes a strong deformation of the hub vortex far downstream the slipstream contraction. This process contributes to the pressure generation at the shaft rate frequency.

Introduction

In the last years, the accurate analysis of the fluctuating pressure and velocity fields, induced by a marine propeller, is required by the increase of both the power of the ship and the demand for a 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 the 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 correlated to the resonance of decks and bulkheads.
The problem of reducing propeller induced noise and vibration leads to an increased complexity of blade geometry, primarily due to the low aspect ratio and to the skew, and have implied a rising interest on detailed measurements of the propeller flow field, to be used for both new design approach as well as for analysing propulsive, hydro-acoustic and structural performances.
The pressure on the stern bottom of the hull, generated by a propeller, is strictly related to the induced velocity field, therefore a detailed flow field analysis, relating the flow structures and the pressure signal, is required to improve the knowledge on the noise mechanism.
On the other hand, the experimental investigation provides baselines to improve and integrate theoretical predictions and to support the flow modelling and the validation of computational codes (BEM, RANS, LES).
The flow field analysis around a propeller is complicated by many factors as unsteadiness, three-dimensionality, and high levels of turbulence. These properties has been pointed out in many previous Laser Doppler Velocimetry (LDV) measurements ([1], [2], [3], [4], [5]), but none of previous studies have been aimed in correlating the velocity field with the pressure signal. In the present study the pressure signals were correlated with the flow structures of the propeller slipstream, like the tip and hub vortex and the blade wake. The correlation between the velocity field and the pressure at a point is performed by using 2D-PIV and hydrophones.
A Wageningen modified type model propeller (INSEAN E779A) was selected for the present research project for two main reasons. First, this model propeller has been widely studied with the most advanced flow measurement and visualization techniques, such as LDV ([3], [5]) and PIV [6]. A large amount of data has been collected providing a thorough documentation on the non-cavitating flow characteristics: the propeller geometry, LDV data and PIV data are now freely available for downloading at http://crm.insean.it/E779A.

Facility and propeller model

Measurements were conducted in the Italian Navy Cavitation Tunnel (C.E.I.M.M.) This is a close jet tunnel with a 2.6 m long by 0.6 m span by 0.6 m deep test section. Perspex windows on the four walls enable optical access.
The nozzle contraction ratio is 5.96:1 and the maximum water speed is 12 m/s. The highest free stream turbulence intensity in the test section is 2% and, in the adopted test condition, reduces to 0.6% in the propeller blade inflow at 0.7 r/R, being r the radial coordinate and R the propeller radius. In the test section, the mean velocity uniformity is within 1% for the axial component and 3% for the vertical component.
The four blades propeller model E779A is skewed, with a uniform pitch (pitch/diameter=1.1) and with a forward rake angle of 4° 3". A reference system O-XYZ, with the X axis along the tunnel centerline, the Y axis along the upward vertical, the Z axis along the horizontal towards starboard is adopted.
Two dimensionless groups govern the propeller flow field in non-cavitating conditions: the advance ratio $J=U_\infty/2nR$, where U_∞ is the free stream velocity, n the revolution frequency and 2R the diameter of the propeller, and the Reynolds number $Re=C_{0.7}V_{0.7}/\upsilon$, where $C_{0.7}$ and $V_{0.7}$ are respectively the cord of the blade and the velocity at 0.7 r/R and υ the kinematic viscosity.

PIV measurements experimental set up

A sketch of the PIV experimental set up is reported in figure 1. The propeller model is mounted on a front dynamometer shaft. This arrangement of the propeller and the length of the test section, which is about 15 times the propeller diameter, allows the slipstream to develop freely in the downstream direction as in a real operative condition. An encoder, with a resolution of 0.1°, mounted on the dynamometer shaft, feeds a special signal processor which provides a trigger signal to a special synchronising device for each propeller angular position. The synchroniser provides a TTL trigger signal to a cross-correlation camera (1008 by 1018 pixel), and to a double cavity Nd-Yag laser (200 mJ per pulse at 12.5 Hz each), to allow image acquisitions for each propeller angular position. The digital cross-correlation video camera, allows the recordings of two separate images (one for each laser pulse) within a few microseconds at a maximum camera frame rate of 15.0 Hz. By using cross-correlation, the directional ambiguity is completely removed. The instantaneous velocity fields were acquired from a distance up to 700 mm from the side window, using a 60 mm lens with 2.8 f-number and imaging an area of about 100 mm by 100 mm.

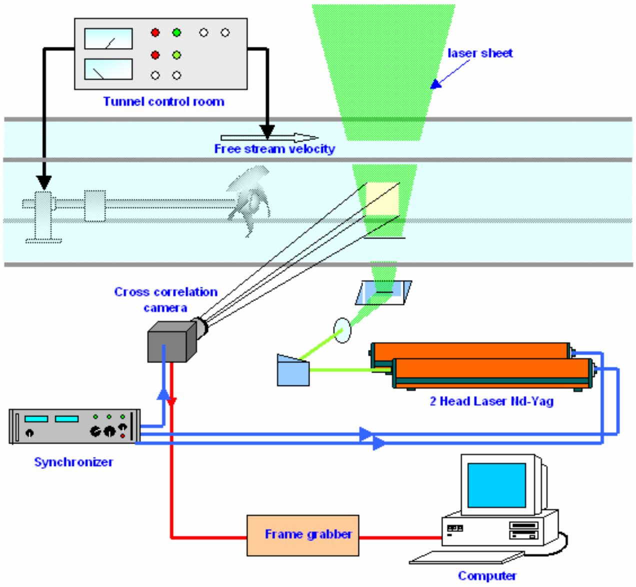

Figure 1. PIV measurements experimental set up.

The tracer particles are one of the critical aspects of the PIV technique, especially in case of large facilities. Since the technique is based on the measurement of particle displacement, it is fundamental that the seed accurately follows the water flow velocity. This requires particles having a diameter on the order of some µm. At the same time, it is mandatory to achieve a high uniform seeding density in the region of interest, at least 15 particle pairs per interrogation window, in order to accurately perform auto/cross correlation analysis. To this purpose, the water in the tunnel was initially filtered, and then seeded with 10 µm silver coated hollow glass spherical particles with high diffraction index and density of about 1.1 g/cm^3. The PIV system was arranged to measure, in the mid longitudinal plane of the propeller, the axial and vertical velocity components simultaneously in the tunnel frame. In view of the symmetry of the propeller inflow and of the steady conditions, when the light sheet is located on the vertical radius (along the z-axis), the axial component of the velocity and the vertical one correspond respectively to the axial and the radial components in the propeller moving frame.
To investigate the propeller wake up to 2 diameters downstream the blades trailing edge, the measurements were performed over 3 adjacent windows by traversing the camera (with an accuracy of about 0.1 mm). The initial reference position was fixed with an accuracy of about 0.5 mm by imaging a special target device.

Pressure measurements experimental set up

Pressure measurements have been performed by using hydrophones (Bruel & Kjaer 8103 models), with a frequency response flat till 20 kHz and a diameter of 3.5 mm. These transducers are sensitive to the pressure fluctuations in the range form 0.3 Hz to 20 kHz, and hence are capable to measure the fluctuations of the total pressure. Hydrophones have been mounted on a special rake device, shown in figure 2. The transducers outputs were amplified by four conditioner-amplifiers Bruel & Kjaer 2650 with band pass filter (0.3 Hz÷20 kHz), connected with the acquisition system and a spectral analyzer. Simultaneously, the TTL signal was acquired to synchronize the angular position of the reference blade. The hydrophones signals were acquired for 50 s at the sample rate of 40 kHz.
The pressure measurements were performed at four radial and eight longitudinal positions downstream the propeller model. Pressure signals acquisition was performed at different propeller conditions J=0.748, 0.814, 0.880, 0.940, 1.012 that correspond to Re (Re x 10^6) 1.14, 1.15, 1.17, 1.80, 1.20. Correlation between pressure signal and velocity field has been performed only for J=0.88.

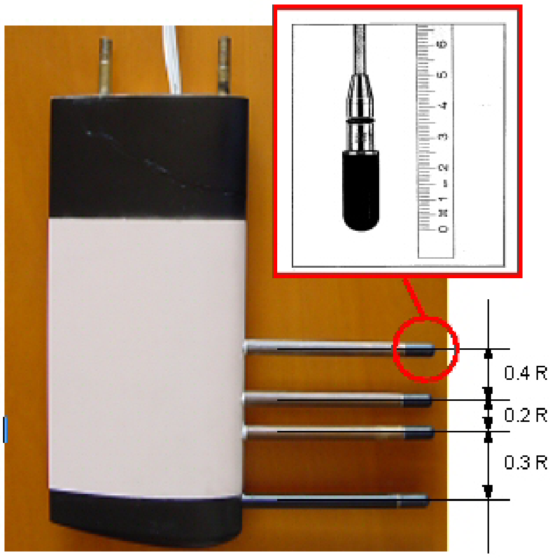

Figure 2. Hydrophones arrangement.

Experimental results

In the following we will focus on pressure measurement results and in the correlation of the pressure signal with the flow structures.
More information about the flow field measured by PIV can be found in [6].
Figure 3 shows the pressure coefficients at different radial positions, for the longitudinal station x/R=1.0. The signals show a different behavior and amplitude as a consequence of the different interaction with the flow structures of the propeller wake.
An example of the pressure signals and the flow field measured by PIV for the angular position θ= 20° is reported in figure 3 (where θ denotes the reference blade angular position).

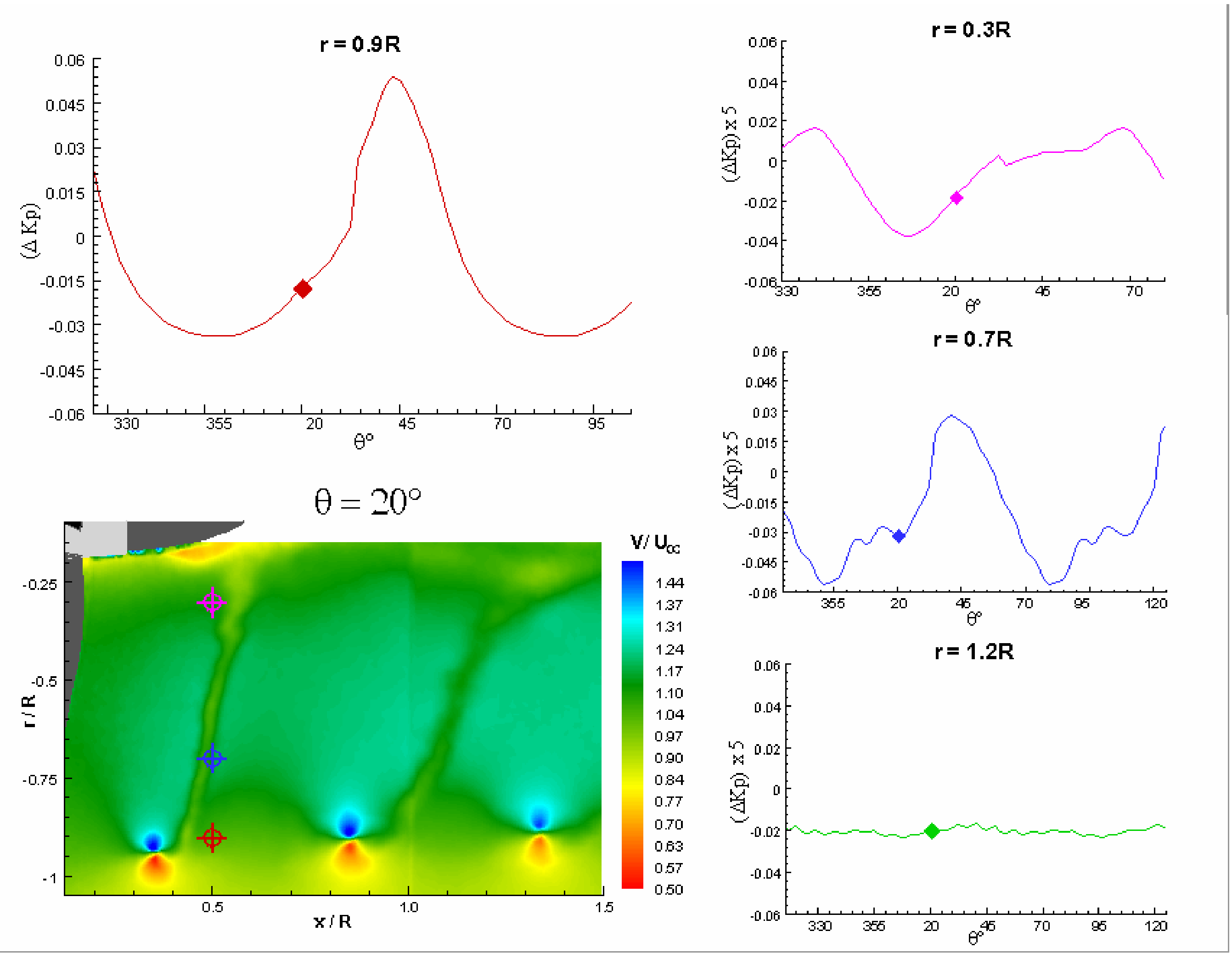

Figure 3. Correlation between velocity field, by PIV images, and pressure signal at θ=20°.
The longitudinal station corresponds to x/R=1.0.

The contour plot represents the magnitude of the in-plane velocity components normalized with the freestream velocity. The main flow structures, like the viscous wake shed from the blade trailing edge, the tip and the hub vortex, are clearly apparent.

In the same figures the pressure at the hydrophones locations is also highlighted. Specifically, the plots report the angular variation, at different radial positions, of the pressure coefficient fluctuations Δk_p defined as:

$$\Delta k_p = \frac{\Delta P}{\rho \cdot n^2 \cdot D^2} \qquad (1)$$

where ΔP is the total pressure fluctuations. It is shown that the pressure signal at r/R=0.3 is influenced by the blade wake passages and by the hub vortex evolution. In the same way, at r/R=0.7, the signal consists of large scale fluctuations caused by the passage at the hydrophone location of the low pressure flow, coming from the face of the propeller and small scale fluctuations due to the passage of the blade wake.

The maximum values of the pressure coefficient are achieved at r/R=0.9 simultaneously to the passage of the tip vortex core, pointing out that the tip vortex is the most important pressure fluctuations source in the propeller wake at x/R=1.0. In fact pressure fluctuation peaks are one order of magnitude larger at r/R=0.9 with respect the other locations. At r/R=1.2 the pressure fluctuation is very low being the transducer out the slipstream tube. Close to the trailing edge of the propeller and for all the radial positions the pressure signals are dominated by the blade rate.

The described behaviour changes downstream the contraction due to the vortex breakdown mechanism. At this purpose, figure 4 shows the amplitude of the blade rate and shaft harmonics, for the radial position r/R=0.3 (top of figure 4) and r/R=0.9 (bottom of figure 4). The analysis points out that near the hub (r/R=0.3), 2-3 diameters downstream the propeller, a different mechanism is contributing to the generation of the pressure signal. In fact the transfer of the energy from the blade to the shaft rate harmonics is strictly related to the vortex breakdown mechanism, as shown in [6]. Downstream the contraction a separation of the trajectory of the tip vortices, due to the different blades and a strong spiralling and deformation process of the hub vortex, occurs. The slipstream starts to lose its axis-symmetry and blade periodicity but in the first phase of the breakdown still maintains the phase with the shaft revolution. This behaviour is probably due to the mutual tip-hub vortex interaction, as demonstrated by their simultaneous generation.

The phase analysis of the correlation between the turbulence field with the standard deviation of the pressure signal $(\Delta k_p)_{std}$ has been also conducted. An example of the achieved results is reported in Fig. (5).

This analysis outlined the following points clarifying the wake characteristics:

1. The highest values of the pressure standard deviation are related to the highest values of the turbulence intensity and mainly concentrated, for r/R=0.9, in the tip vortex core;

2. Turbulent blade wake, downstream of the propeller, is quickly diffused and dissipated by viscous effects. Nevertheless the standard deviation plots show two peaks associated respectively to blade wake and tip vortex passages. The maximum values are achieved in correspondence of the tip vortex core;
3. The standard deviation of the pressure fluctuation in the downstream direction raises as a consequence of the largest turbulent fluctuation achieved in the tip vortex core far downstream the propeller. This effect is related to the vortex breakdown instability as shown in [6].

Conclusions

The performed experimental study allows correlating the propeller flow field structures, like the blade wake and the tip vortex, with the pressure signal at a point. The results point out that, within the slipstream contraction, the highest values of the pressure fluctuations are in correspondence of radial position x/R=0.9, in coincidence with the tip vortex passage. Thus this flow structure is the most important one in generating the hydrodynamic pressure field in the propeller flow.

Far downstream the slipstream contraction the vortex breakdown occurs and the strong deformation of the hub vortex contributes in the pressure signal generation at the frequency of the shaft rate.

The standard deviation of the pressure signal shows the presence of two peaks, with different intensity, due to blade wake and tip vortex passage. Furthermore, the increased values of the standard deviation in the downstream evolution point out the vortex instability phenomena as also shown by the turbulence distribution.

Acknowledgments

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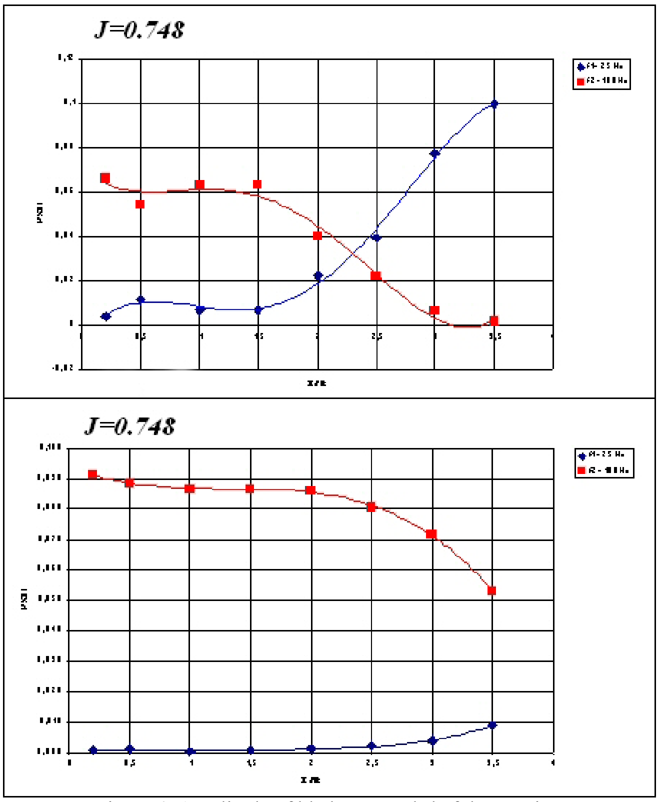

Figure 4. Amplitude of blade rate and shaft harmonics.

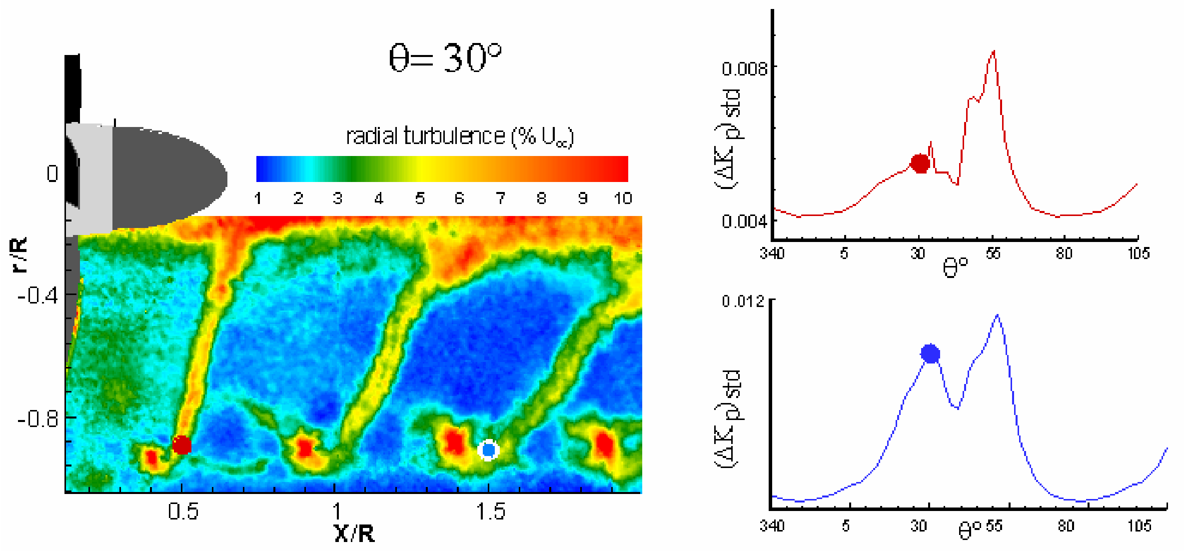

Figure 5. Correlation between turbulence and pressure signal standard deviation at θ=30°.