Experimental investigation of propeller performance in straight and steady drift motion by single blade load measurements and boroscope-based SPIV

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ABSTRACT

A marine propeller operating in off-design conditions is a challenging topic in marine hydrodynamics that has attracted a strong interest in the last decades from industry and research institutions. During actual ship operations, disturbances in the propeller inflow have a negative impact on a wide range of aspects: from reduced overall efficiency up to the structural failure of the propulsion system. In this work, the relation between propeller loads and its inflow in off-design conditions is investigated by means of two novel experimental set-ups developed to analyze each of these aspects, respectively an onboard system to measure single-blade loads, and a boroscope-based stereo-PIV system for the flow characterization. The latter methodology allows underwater acquisitions and improves greatly upon the design introduced by Pereira et al (2003). However, this concept introduces strong optical aberrations which have to be dealt with appropriate algorithms. The whole apparatus is used for towing tank testing of a twin-screw model in straight-ahead and steady-drift conditions. Preliminary results obtained in straight-ahead and steady-drift conditions (drift angle $\beta = 13^\circ$) are reported to show the potential of the developed measurement methodology for drawing a comprehensive picture of the propeller performance.

Keywords

Propeller performance, load measurements, SPIV, boroscope.

1 INTRODUCTION

Marine propeller plays a pivotal role on the development of ship design. Traditionally, the design and analysis of marine propeller are focused on the ideal case of straight motion in calm water; however, in actual operative conditions, the motion of the ship can be different due to environmental factors (waves and wind), counteracting control actions (i.e., autopilot) and maneuvering. In these cases, the cross flow induced by the motion and the consequent modification of the viscous wake of the hull alter the blade hydrodynamics and, consequently, the resultant propeller loads. The thorough assessment of the problem is very challenging, because the evolution of the inflow to the propeller depends on geometric details of the stern shape, appendages configurations (in case of multi-screw driven ships) and direction of rotation of the propulsors and is strongly coupled with the kinematic response of the body. Generally speaking, the flow impinging the propeller undergoes a speed drop caused by the waves or maneuvering related motion and is dominated by the simultaneous presence of coherent structures and large flow separation regions. As a matter of fact, the propeller develops higher thrust and torque, and, more importantly, relevant in-plane forces and moments are generated as a consequence of non-uniformity of the inflow over the propeller disk that further stress the propulsion system (shaftline and bearings) and hull structure. In fact, an earlier analysis for a limited series of twin screw naval ships at full scale highlighted that the power absorption of the external propeller (i.e., on the windward side) was almost doubled with respect to the internal one (on the leeward side) and exceeded by about 80% the value in the rectilinear navigation (Coraddu et al (2013)). Systematic investigation performed on a free running maneuvering twin screw model highlighted that the in-plane loads (lateral force and vertical force) during maneuver can achieve up to 30% the value of the thrust in the straight ahead motion during tight maneuvers. Similar values can be experienced during transient or maneuvering at lower rudder angle due to interactions of propeller blades with coherent structures detached from the bilges and appendages of the hull (Ortolani et al (2015a)). This aspect highlights the fact that the off-design condition can be differently experienced at low and high rudder angle, depending of the flow features that characterize the propeller inflow. Although an increased level of attention is paid to the understanding and quantification of the propeller performance in off-design condition, studies (both numerical and experimental) are limited and mainly focused on idealized conditions for the isolated propeller (Dubbioso et al (2013)). In this work, the cause-and-effect relation of the propeller performance and the inflow in off-design condition has been investigated for a self-propelled twin screw model equipped with two novel set-up for the measurements of the flow field and single blade loads. The set-up of the single blade load measurements was applied to the same model for free running maneuvering experiments and provided high quality results (Ortolani et al (2015a), Ortolani et al (2015b)). The methodology chosen for inflow analysis is the boroscope-based Stereo Particle Image Velocimetry. The application of Particle Image Velocimetry and its stereoscopic version (SPIV) for the analysis of naval prob-
lems is found in early works by Pereira et al (2003) and Calcagno et al (2005). The main operating difficulty is the usually unfavourable optical access conditions, which is usually addressed by using water-proof casings to protect acquisition equipment. An underwater modular, versatile system for Stereo PIV measurements based on this approach was proposed and successfully used by Pereira et al (2003) in towing tank testing. The methodology presented builds on this knowledge by employing boroscopes as the optical piece of equipment in the stereo PIV system rather than typical objective lenses. The advantages of the proposed methodology are low intrusivity, high portability, ease of calibration. More importantly the set-up approach does not make it necessary to develop ad-hoc water-proof casings to host cameras and other equipment.

2 EXPERIMENTAL SET-UP

In this section the overall towing-tank set-up is described along with the two novel acquisition systems to measure single-blade loads and propeller inflow by using boroscope devices.

2.1 Model set-up and test matrix

Tests are carried out in the CNR-INM towing tank facility, depicted in Fig. 1. The towing tank features a 475 m long, 13.5 m wide and 6.5 m deep basin. The tank carriage can be driven at up to 15 m/s with an accuracy of 1 mm/s and speed fluctuations within 3%. A fiberglass twin screw ship model without propellers and rudders is employed in the tests. The drift angle $\beta$ between the model axis and the direction of motion of the carriage can be set with an accuracy $0.1^\circ$. Experiments were carried out in straight ahead (i.e. $\beta = 0^\circ$) and steady drift motions ($\beta = 13^\circ$) with the aim to represent weak and tight maneuvering conditions. Acquisition are related to the internal, i.e. leeward side propeller. The corresponding Froude number based on model length is $Fr = 0.24$. For each run a set of 400 image pairs was acquired. The schematics of towing tank set-up along with the reference frame for the drift angle is provided in Fig. 1.

2.2 Stereo PIV system

In this work we present a novel approach which improves upon the state-of-the-art of PIV measurements in towing-tank by relying upon boroscope equipment rather than usual camera lenses. An Olympus 800 mm long, 16 mm diameter tube, 60 view angle, rigid borescope was employed for the experiments described in this document. The choice of a rigid and relatively large diameter addresses the requirements for minimization of optical aberrations and maximization of incoming light. Two TSI Powerview 8MP cameras featuring a resolution of 3320 x 2496 pixels are used with a 532nm wavelength Evergreen Nd:YAG laser unit, max pulse energy 200 mj, repetition rate 15 Hz. We point out that the only components which are underwater during acquisitions are the boroscope tubes and the light sheet forming equipment. Cameras are arranged at an angle of respectively $\alpha_1 = 50^\circ$ and $\alpha_2 = 80^\circ$ with respect to the acquisition plane and looking at the same side of it. Both cameras are located R=800 mm from the acquisition plane. Measurements are carried out without the propeller with acquisition plane located approximately 1 mm downstream of the rightside propeller hub. The measurement area has a size of 430 mm X 260 mm, is located approximately 1mm downstream of the propeller hub and centred on it, as shown in Fig. 3.

2.3 Instrumented Propeller

The presented set up features a custom–instrumented propeller, designed to measure the whole system of loads (3 forces and 3 moments) acting on a single blade. With this purpose, a 6 components, off-the-shelf transducer, support-
ing one of the blades, has been housed inside the propeller. High quality, low-noise and low-resistance slip rings carry over power supply and data signal from transducer channels to the acquisition system. The instrumented propeller is the starboard one.

3 DATA ANALYSIS

3.1 Stereo PIV measurement

The full three component velocity field is attained by following a series of steps: calibration, image pre-processing, cross-correlation, vector validation and reconstruction. The whole process is carried out with the commercial software Insight 4G by TSI inc. SPIV calibration is carried out with a four-plane calibration target, 300 x 300 mm size, inter marker distance 10 mm with distance between planes in the axial direction equal to 1 mm. Using a two-plane target allows a 3-D calibration to be performed without the need to traverse the target (Adrian and Westerweel (2011)). Validation of the Stereo PIV system was carried out by a series of free-stream runs performed without the model ship. Average deviation from the reference free-stream speed was below 5%. The towing-tank set up for validation of Stereo PIV apparatus is shown in Fig. 4. Image conditioning is carried out in order to improve the effectiveness of the following cross-correlation step. Background-subtracted images are fed to a dewarping engine to address the perspective deformation introduced by the cameras view angle and the boroscope lenses. This module applies a dewarping correction algorithm based on a selected window function and resamples the processed images. The algorithm employed in the cross-correlation step implements an iterative multi-pass, multi-grid, image deformation scheme with window-offset (Scarano et al (1999), Scarano et al (2001)). Sub-windows grid resolution is set to 128 x 128 pixels for the first pass and 64 x 64 pixels for the second and final passes. The resulting vector grid spacing is 32 pixels (a sub-window overlap of 50 was set), which corresponds to approximately 3 mm.

Uncertainty was assessed taking into account three sources: the correlation errors in the two-dimensional displacement calculation; the stereoscopic three-dimensional reconstruction errors; the light-sheet calibration target misalignment error. A calibration correction algorithm (Wieneke (2005)) was adopted to address this source of error and the presented data can be considered unaffected by it. An estimate of the overall measurement uncertainty is thus obtained by taking into account the first two error sources. A value usually agreed for the two-dimensional correlation uncertainty, evaluated as the root mean square (RMS) of the particle displacement, is 0.1 pixel (Raffel et al (2018)). For the assessment of the reconstruction error we follow the approach where the RMS of the velocity field is a function of the cameras angle with respect to the acquisition plane and the mentioned correlation-noise uncertainty. For details about this method refer to Falchi et al (2014) The resulting uncertainties for the three distinct velocity components are then

$$\text{RMS}(u)/U = 1.3\%,$$

$$\text{RMS}(v)/V = 2.5\%,$$

and

$$\text{RMS}(w)/W = 0.7\%,$$

where lower case and upper case letters are instantaneous and time average quantities. Statistical convergence of the average measurements is assessed by considering the standard deviation of the mean and a Student distribution with a confidence interval of 95%. The uncertainty of the average value is calculated as not exceeding 3.1% for the streamwise component and 4.4% and 5% respectively for the velocity components along longitudinal and vertical directions.
3.2 Force Measurement

Loads measurements, specifically forces ($T_{xyz}$) and moments ($Q_{xyz}$), are attained by the transducer housed inside the hub; the device has its own reference frame, centered on the top surface, at the contact with the blade root. With reference to figure 6, two additional frames have been adopted in order to have data consistent with the conventional frame centered along the shaft, at the mid-plane of the propeller: the first one, called “blade frame” (subscript “B”), rotating with the blade, is defined with $x$ pointing forward, $z$ radially outward and coincident with the $z$ of the transducer and $y$ determined by right-hand rule; the second one, fixed with the model, is defined with $x$ pointing forward, $z$ radially upward and $y$ to the left, called hub frame (subscript “H”). The position of the blade with respect to the H–frame is identified by $\theta$, that is positive oriented with the sense of rotation and $\theta = 0^\circ$ for the blade at the top–right position.

The period of revolution of the propeller is divided in four sectors, the first one defined for $0^\circ < \theta < 90^\circ$, and so on.

Data from transducer frame have been expressed in the rotating frame by appropriate conversion formulas. The measured loads result from the contribution of inertial loads and hydrodynamic loads. The analysis was carried out only on hydrodynamic loads, properly derived from the total one subtracting the inertial contribution (centrifugal and gravity sources). The loads are presented in the usual non–dimensional form, i.e., the forces and moments are made non–dimensional by factors $\rho N^2 D^4$ and $\rho N^2 D^5$, respectively, where $D$ is the diameter, $N$ is the propeller rate of revolution (RPS) and $\rho$ is water density.

4 RESULTS

4.1 Straight ahead motion

In this section we show the results of the straight ahead motion test case. In Fig. 7 to Fig. 13 the normalized average components of the velocity field along with the turbulence intensity of each component are provided. The wake features a positive, i.e. upwards, velocity over most of the area of the propeller disk (highlighted by a red circle) with the exception of a smaller sector in the upper half affected by the disturbance of the hull, shaft and its brackets. This area is characterized by a horizontal component is negligible with respect to the vertical one and is relevant only at the recirculating region around the hub structure. The axial component clearly shows a velocity decay in the hub brackets region and the effect of the hull surface in the upper area of the measurement plane. The patterns of turbulence intensity shown in Fig. 11, Fig. 12 and Fig. 13 are similar with respect to the region downstream of the hub brackets, with the trace of the latter which is evident in the pattern of turbulence. Additionally, the axial component is characterized by a turbulence level which is approximately two times higher than for the other components. The above findings show that at straight ahead motion the hull wake is mostly affected by the wake stemming from the hub brackets.

During straight ahead motion, as reported in figure 10, blade thrust and side force (and related moments, not reported) are larger in the upper half of the disk and decrease in the lower half and experience the same trend, being directly related to the incidence of the blade sections. During the downstroke motion of the blade ($0^\circ < \theta < 180^\circ$), the loads experience two peaks that are associated to two different features of the wake: the first peak, at approximately $\theta = 60^\circ$, is caused by the defect of the axial velocity $U$ associated to the inward bracket, whereas the second one ($\theta = 110^\circ$) is ascribed to the increase of the tangential velocity relative to the blade sections due to the upwards tangential velocity ($U$ is almost undisturbed). Approximately in the $4^\text{th}$ quadrant, the loads again increase due to the encounter of the wake of the brackets and hull. The spindle moment $Qh,z$ is always positive, namely it acts to reduce the pitch angle of the blade according to the assumed reference frame; moreover, it increases during the unloading of the blade and vice–versa.
4.2 Steady drift: internal propeller

Tight maneuvering conditions are investigated in this section by looking at the propeller inflow in conditions characterized by steady drift motion. As the investigated propeller is on the starboard side, analysis of internal propeller is presented. The analysis of the velocity field provided in Fig. 14 to Fig. 20 give evidence of dramatic modifications undergone by the hull wake. The mean horizontal
component is positive in the lower quadrants, as the flow is predominantly tangential at this drift angle (vertical component is slightly positive) whereas it vanishes in the upper quadrants. In particular a region in the upper left quadrants is affected by strong velocity gradients. This area, which is well inside the propeller disk, is also associated to marked gradients in the vertical and axial components and points at the occurrence, on average, of large coherent structures supposedly detaching from the hull appendages and affecting the propeller inflow. The observation of the axial components conveys that also the lower left quadrant features a marked velocity decay which could be due to the wake of the windward side hub shaft.

Although also the vertical component features such an area, observation of Fig. 19 shows a clear evidence of the shear layer developing from the lower side of the hub. Furthermore, the increase of fluctuations in the upper left quadrant which is reported for all of the velocity components, which matches the recirculating region reported by the mean data discussion, suggests that a large three-dimensional coherent structure is affecting the flow field at this drift angle.

![Figure 14: Normalized mean horizontal component. Steady drift.](image1)

**Figure 14:** Normalized mean horizontal component. Steady drift.

![Figure 15: Normalized mean vertical component. Steady drift.](image2)

**Figure 15:** Normalized mean vertical component. Steady drift.

Analysis of the turbulence intensity given in Fig. 18, Fig. 19 and Fig. 20 shows several flow region where an increase of turbulence intensity is reported. The horizontal component turbulence intensity is characterized by a large region, which extends from the upper side of the hub and reaches as far as the 3/4 of the propeller disk, where a relatively higher levels of fluctuations are reported. A matching area is found in the axial component, pointing at the effect of the wake developing from the windward side hub brackets, that at this drift angle projects over the hub itself.

Single blade forces, provided in Fig. 17 are remarkably affected by such coherent structures that alter the relative blade–inflow incidence angle. The interplay between the blade and the coherent structures is evidenced by the sudden rise of thrust and side force at $\theta = 60^\circ$. With respect to the maximum values observed at $\beta = 0^\circ$, the increase corresponds to about 60%. For $< 90^\circ < \theta < 300^\circ$ the loads quickly drop because the tangential velocity relative to the blade is reduced due to the cross flow induced by the drift motion. In a similar fashion to the rectilinear motion, the loads again increases in the last sector of the cycle as a consequence of the velocity reduction associated to the wake of the external bracket and hull. The blade spindle torque $K_{Qz}$ shows the same features observed for the previous case namely, it increases when the blade loading diminishes. In this case, during the blade/vortex interaction, $K_{Qz}$ changes sign, i.e. the hydrodynamic centre of loads moves towards the leading edge.
CONCLUSIONS

In this work, the relation between propeller loads and propeller inflow in off-design conditions, characterized by steady drift motion, is investigated by means of two novel experimental set-ups. The results presented show that the methodologies have a strong potential for towing-tank applications which aim at gaining a deeper understanding of the interactions between propeller loads and inflow features. In particular, at $\beta = 14^\circ$ the internal propeller inflow shows marked modifications due to the effect of vortex structures detaching from hull appendages and affecting the left-side propeller disk. Loads and moments measurements confirm that the latter occurrence has a relevant impact on blade loads, for which a considerable rise is reported; this is consistent with marked modifications of the blade inflow angle induced by the steady drift motion.

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REFERENCES


