Hull wake measurement in steady drift using a boroscopic stereo-PIV system

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Abstract. Particle Image Velocimetry measurements in towing tanks usually require ad-hoc solutions to address the need to protect electronic equipment from water. Pioneering works in this field rely upon fully underwater probe systems to address this issue, as in [1]. In this work we present an approach based on the use of endoscopic equipment (boroscopes) to carry out towing-tank Stereo PIV (SPIV) measurements of the hull wake of a ship model in steady drift. A boroscopic SPIV system provides increased flexibility thanks to the absence of water-proof camera casings. The only underwater components of the presented apparatus are the boroscope tubes and the light-sheet forming device, which are not critical in terms of water protection. The major drawbacks are the reduced light-collecting efficiency of the boroscope devices as well as the geometric deformations and aberrations due to the short focal length, which must be specifically addressed with adequate algorithms. The boroscope-based SPIV system presented in this work features three cameras for redundancy and to increase measurement accuracy. We present the results of towing-tank testing of the hull wake of a twin-screw model at Froude number Fr = 0.24 in straight-ahead and steady drift conditions.

1. Introduction
The importance of a thorough understanding of the flow around a naval vessel for the design process has been known since decades. In spite of this, the available experimental data are often partial and limited in their scope. A specific aspect which has recently attracted a growing interest is the investigation of the off-design conditions in sea operations. Disturbances to the propeller inflow due to deviation from nominal behavior, i.e. tight maneuver or straight motion at high drift angles, have a detrimental impact on a wide range of aspects such as reduced overall efficiency, cavitation-induced pressure pulses, vibration, noise and structural failure of the propulsion system.

In particular, twin-screw ships operations are specifically affected by wake asymmetry which develop in off-design conditions. In [2] and [3] the Authors investigate on the asymmetric propeller behavior, and its impact on maneuverability, for a twin-screw vessel by free-water testing and numerical simulations. To the Authors' knowledge, experimental data on twin-screw vessels in off-design conditions are still lacking. In this work we aim at improving the understanding of the modifications underwent by the hull wake under off-design conditions represented by steady drift motion, with a focus on the different impact on windward and leeward propeller inflow. The inherent difficulties which needs to be overcome in order to carry out such measurements require the development of advanced experimental techniques.

The use of advanced techniques for optical whole-field velocity measurements in the naval field has recently seen a marked development. Examples of applications of PIV to the analysis of naval problems...
are found in the early works by [4] and [5]. As a matter of fact, in naval hydrodynamics studies, the underwater requirement is usually mandatory for the image-capturing devices. To the Authors knowledge, all of the literature works on the subject address this issue by making use of ad-hoc designed water-proof casings to protect acquisition equipment. An underwater modular, versatile system for Stereo PIV measurements based on this approach was proposed and successfully employed by [1] in towing tank testing. The modular structure allows for different configurations with respect to number of cameras and view angle. Although these measurement systems have proven to be effective for towing tank use, their development and manufacturing is time-consuming and requires non-negligible economic efforts.

To this aim we propose a novel approach which relies upon the use of boroscopes as the optical piece of equipment in the stereo PIV system rather than typical objective lenses. Use of endoscopic equipment represents a valuable choice whenever standard methods are not viable but specific downsides should be accounted for. Firstly, the amount of light entering an endoscopic device is considerably lower than that involved when using a common lenses. The second main drawback stems from the short focal length of the endoscopes, which leads to a marked perspective deformation of the acquired images.

By building on this experience, in this work we propose a boroscope-based stereo PIV system for the investigation of the hull wake of a twin-screw model ship in steady-drift conditions. 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. It therefore stands as valuable alternative to curb development and testing costs. Furthermore, the size and weight of the apparatus make it possible to mount it directly onto the model. This feature stands as a distinct advantage when complex ship dynamics are to be investigated.

2. **Experimental set-up**

The components of the Boroscope Stereo PIV (SPIV) measurement apparatus are shown in Figure 1. Camera model is TSI Powerview 8MP, 3320 x 2496 resolution, dynamic range up to 14 bit and quantum efficiency 48% at 480nm wavelength. The laser is an Evergreen Nd:YAG unit, max pulse energy 200 mJoule, wavelength 532 nm, repetition rate 15 Hz. An Olympus 800 mm long, 16 mm diameter tube borescope with view angle of 35° and focus range from 20 mm to infinity is employed.

![Figure 1: Boroscope SPIV system](image)

The boroscope eyepiece is connected to the acquisition cameras via a C-mount adapter. A fin-like structure encloses the optical elements for laser sheet formation. The fin-like structure and the terminal end of the boroscopes tubes are the only pieces of equipment which are underwater during operations.
Although only two cameras (labelled as A and B) are necessary to perform stereo reconstruction we propose a set-up featuring a third additional camera (C). This is placed facing the opposite side of the acquisition plane with respect to the other two, at the same distance from the acquisition plane center. The three cameras angles with respect to the measurement plane are $\alpha_a=50^\circ$, $\alpha_b=80^\circ$ and $\alpha_c=45^\circ$ respectively. The redundant additional information obtained from camera C has beneficial effect on measurement accuracy. In fact each of the possible three pairs of cameras (namely A-B, B-C, A-C) is associated to a specific calibration procedure and to a partly independent vector field reconstruction.

The area where the full three component velocity field $\mathbf{V} = (u,v,w)$ is measured has a size of 430 mm X 260 mm and is centred on the propeller's hub and approximately 0.5 mm downstream of hub face. A reference system is defined accordingly, as shown in Figure 2.

Figure 2: SPIV measurement reference system

At the tank carriage front a rake of three seeding generators is installed to attain flow seeding, by means of microbubbles generated by cavitation. Calibration was carried out with a four-plane calibration target, 300 x 300 mm size, inter marker distance 10 mm with distance between planes in the z direction equal to 1 mm.

The outcome of the calibration step was validated by a series of free-stream runs performed with the SPIV apparatus connected directly to the towing tank carriage. The average deviation of the measured velocities from the reference free-stream speed was between 3% to 5%, with the latter figure reported in the outer image regions, as expected.

The full three component velocity field is obtained with the commercial software Insight 4G by TSI inc. The algorithm employed implements an iterative multi-pass, multi-grid, image deformation scheme with window-offset [7],[8]. Optimal 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 overall resolution.

Before cross-correlation computations, 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. Bicubic interpolation paired to a Hamming window was chosen as the most effective in terms of beneficial effect on the correlation calculation and computing time.
Uncertainties in measurements is assessed by taking into account three distinct sources of error: the correlation errors in the two-dimensional displacement calculation; the stereoscopic three-dimensional reconstruction errors; the light-sheet calibration target misalignment error. The latter is not taken into account here since a calibration correction algorithm was employed ([9]). An agreed value for the two-dimensional correlation uncertainty, evaluated as the root mean square (RMS) of the particle displacement, is 0.1 pixel ([10]). For the assessment of the reconstruction error we follow the approach of [6]. The RMS of the velocity field is then estimated as a function of $\alpha$ and the mentioned correlation-noise uncertainty. The resulting relative errors, defined as the ratios of the RMS of the instantaneous velocity components to the average values, are given in Table 1.

| Camera Pair | RMS(u)/U | RMS(v)/U | RMS(w)/U |
|-------------|----------|----------|----------|
| A-B         | 0.013    | 0.025    | 0.007    |
| B-C         | 0.009    | 0.0178   | 0.007    |
| A-C         | 0.013    | 0.021    | 0.007    |

Table 1: Relative errors for each velocity component based on camera pair

Tests are carried out in the CNR-INM towing tank facility, whose data are reported in Figure 3, along with overall set-up. The drift angle $\beta$ between the model axis and the direction of motion of the carriage can be set with an accuracy of 0.1°. Experiments were carried out in straight ahead (i.e. $\beta = 0^\circ$) and steady drift motions with the aim to represent weak and tight maneuvering conditions.

Steady drift conditions were tested for $\beta = 8.4^\circ$ and $\beta = \pm 13^\circ$. Tests were performed at Froude number $Fr = 0.24$ based on carriage speed $U_0$ and ship model length. All acquisitions were carried out without the propeller.

We point out that positive and negative drift angles match respectively a starboard and a port side turn, therefore the propeller inflow features will be respectively representative of an internal and external propeller.

3. Results

The average of the velocity components $U = \langle u \rangle$, $V = \langle v \rangle$ and $W = \langle w \rangle$ within the measurement plane, normalized with respect to free-stream speed, are provided in Figure 4, Figure 5 and Figure 6 respectively. The projection of the propeller disk onto the acquisition plane is depicted as a black circle.
3.1. Nominal wake

Results show that the propeller inflow is markedly perturbed by the forward and astern brackets and the hull boundary layer. This is particularly evident from the analysis of the axial component $U$, which is affected by a marked velocity defect in the region above the hub, due to wake stemming from the hub brackets. Along the vertical axis $Z$, the $U$ component is characterized by a drop up to $0.6U_0$, in the outer region, which is due to the hull boundary layer.

Perturbation due to the hub brackets structure is also noticeable by looking at the vertical component, shown in Figure 6, which reports a nearly null $W$ component in the upper quadrants above the hub. In the lower propeller disk region the axial component reaches the free-stream level, whereas the tangential flow is directed mainly upwards. This occurrence is most likely due to the geometry of the stern lines as well as the inclination of the shaft line, as reported by other Authors ([11]). The flow moving upwards in the lower quadrants encounters the hub structure and consequently features a region of converging flow right above it. This scenario is confirmed by looking at the horizontal component, provided in Figure 5, which is characterized by an area of converging flow in the mentioned region.

![Figure 4: Mean axial velocity; nominal wake and internal and external propeller](image)

3.2. Steady drift: Internal Propeller

The inflow to the internal propeller undergoes marked modifications as the drift angle increases. The axial velocity, although still featuring the effect of the hub brackets wake, confirms that at the drift angles tested the flow structures supposedly detaching from the hull appendages have a relevant impact on the flow in the propeller disk projection. Figure 4 shows that at $\beta = 8.4^\circ$ the flow in the upper left
quadrant is deeply impacted by a large recirculating region, as witnessed by the direction of the horizontal and vertical velocity components shown in Figure 5 and Figure 6. This vortex structure could be detaching from the hull skeg and crossing the propeller plane at this drift angle.

The lower quadrants show that the projection of the velocity vector in the measurement plane is directed mostly outwards, as opposed to the nominal wake, though a certain degree of upwash is still reported. As the drift angle increases, at $\beta = 13^\circ$, the disturbance in the upper left quadrants shifts outwards, thus hinting at a lower impact on the propeller operations. On the other hand, the left quadrant is characterized by a velocity defect which is not directly associated to a recirculating flow region.

3.3. Steady drift: External Propeller

Analysis of the external propeller inflow during steady drift motion confirms that for twin-screw ships a wide degree of asymmetry holds when non-nominal conditions are met.

Analysis of the axial velocity reveals that at drift angle $\beta = -13^\circ$, the outer propeller axial velocity is more homogeneous than its internal counterpart. A large area of axial velocity decrease, covering approximately the whole upper left quadrants is directly related to the wake stemming from the hub stem and brackets, whereas as expected the outer flow is relatively undisturbed. This is confirmed by the horizontal velocity field, which is basically a tangential flow. The region close to the hub features a small recirculating region related to the wake developing from the hub.

Figure 5 Mean horizontal velocity: nominal wake and internal and external propeller
4. Conclusions

Results show that the boroscope-based Stereo PIV technique presented is a viable methodology which has the benefit of reducing the cost of development of ad-hoc water-proof equipment for towing tank testing. Further advantages are the high degree of portability and versatility of the measurement apparatus. Drawbacks are related to the low incoming light and strong optical aberrations.

Application of the technique to the investigation of the propeller inflow in a twin-screw model ship in steady drift conditions is presented. Results show that a high degree of asymmetry is reported between internal and external propeller inflow, with the former featuring marked disturbances due to the effect of flow hull appendages already at $\beta = 8.4^\circ$.

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References

[1] Pereira F, Costa T, Felli M, Calcagno, G and Di Felice F 2003 ASME/JSME 2003 4th Joint Fluids Summer Engineering Conference 101-106
[2] Coraddu A, Dubbioso G, Mauro S and Viviani M 2013 Ocean Eng 68 47-64
[3] Muscari R, Dubbioso G, Viviani M and Di Mascio A 2017 Ocean Eng 143 269-281
[4] Longo J, Shao J, Irvine M and Stern F 2007 J Fluids Eng 129 524—540
[5] Calcagno G, Di Felice F, Felli M and Pereira F 2005 Mar Technol Soc J 39 94-102
[6] Falchi M, Felli M, Grizzi S, Aloisio G, Broglia R and Stern F 2014 Exp Fluids 55 1844
[7] Scarano F 2001 Meas Sci And Tech 13 R1
[8] Scarano F and Riethmuller ML 1999 Exp Fluids 26 513-523
[9] Wieneke B 2005 Exp Fluids 39 267-280
[10] Raffel M, Willert CE, Scarano F, Kahler CJ, Wereley ST and Kompenhans J 2018 Springer
[11] Dubbioso G, Muscari R, Ortolani F and Di Mascio A 2017 Ocean Eng 130 241-259