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2D-2C Particle Image Velocimetry analysis of contra-rotating propellers hydrodynamics

Alessandro Capone¹, Alessandro Maiocchi¹, Jais Mohamed¹, Jonathan Tripelli², Giovanni Paolo Romano², Fabio Di Felice¹, Francisco Alves Pereira¹

¹CNR-INM, Institute of Marine Engineering, Via di Vallerano 139, 00128 Rome, Italy

²Università Roma Tre, Via Ostiense 159, 00154, Rome, Italy

alessandro.capone@inm.cnr.it

Abstract. Contra-rotating propellers represent a non-conventional approach for marine propulsion whose main advantage lies in the increase of propulsive efficiency. This is achieved by recovering part of the energy loss due to the rotational flow generated by a single propeller by means of a contra-rotating downstream propeller. The hydrodynamics of such configuration is quite complex due to the interaction between upstream and downstream propellers and a deep understanding of their features is critical to driving the design phase. In this work a methodology based on planar (2D-2C) Particle Velocimetry is presented to investigate on the flow in the wake of two contra-rotating propellers. An ad-hoc mixed hardware and software phase-locking technique is developed in order to analyze the contribution of each propeller to the overall hydrodynamics of the system.

1. Introduction

The need for more efficient marine transportation is currently one of the strongest driving forces in the field of naval research. Among a wide range of approaches to curb fuel consumption contra-rotating propellers (CRP) represent a viable, though non-conventional, option for marine propulsion and from this standpoint they can be considered an energy-saving device. The rationale underlying the CRP design approach is grounded in the observation that the rotational flow induced by a single propeller is associated to a loss of energy which may, at least partially, be recovered by an additional downstream counter-rotating propeller.

Many design parameters play a pivotal role in the resulting CRP system efficiency: propeller geometries, propellers axial distance and diameters ratio. To the authors' knowledge, most of the works on the subject follow an approach to the analysis of a CRP system which is based on the observation of global quantities such as thrust and torque ([1],[2],[3]). As a matter of fact such systems feature an intrinsic complexity stemming from the interactions between the two propellers which poses several difficulties as experiments are to be designed. While investigation of single propeller hydrodynamics has been tackled effectively in the past via phase-locking velocimetry techniques ([4],[5] among others) counter-rotating propellers configuration requires ad-hoc acquisition and post-processing techniques. To this aim, in this work we present an advanced data manipulation scheme based on Particle Image Velocimetry (PIV) which makes it possible the investigation of the complex hydrodynamics which are associated to CRP systems by isolating the contribution of each propeller.



2. Set-up and methods

Measurements are carried out at the Italian Navy Cavitation Tunnel (CEIMM). The facility features a test section of size 0.6 m X 0.6 m X 2.6 m and perspex windows. The contraction ratio is 6:1 and the operating speed range is 2÷12 m/s. Maximum free stream turbulence intensity in the test section is 2% and mean velocity uniformity is within 1% and 3% for the axial and vertical components respectively. Two counter-rotating three-blade propellers with a diameter ratio 0.9 are installed on distinct shafts each one equipped with an encoder with 0.2° resolution. The signal coming from the downstream propeller shaft encoder is acquired by a processing unit and is used as a trigger signal for the acquisition cameras. Upstream propeller diameter D is employed as a reference length to make measured quantities non-dimensional.

A cross correlation CCD PCO Pixel Fly camera (14bit dynamic range, 1392 x 1024 image resolution) is employed for PIV measurements. The field of view is focused on the wake and covers approximately an area of $0.7D \times 0.4D$.

Laser lighting is provided by a Nd:Yag double cavity unit (200 mJ per pulse at 12.5 Hz) and estimated laser sheet thickness is 1.5 mm. Measurements are carried out at fixed advance ratio $J=U_0/nD$ where U_0 and n are respectively the free stream speed in the test chamber and the nominal shaft rotational speed. The seeding is attained with 10 μ m silver coated hollow glass spheres. The overall acquisition frequency is set to approximately 3 Hz.

The velocity field is calculated with the commercial software Insight 4G by TSI inc. Images are background-subtracted and fed to the cross-correlation algorithm. The latter implements an iterative multi-pass, multi-grid, image deformation scheme with window-offset. Interrogation windows for the first, second and final passes are set to 64 x 64 pixels and 32 x 32 pixels, and the resulting grid resolution is 16 pixels (approximately 0.015D). Spurious vectors are dropped according to a local median test on 3x3-points kernel.

Phase-locked schemes are usually employed for investigations on propeller wakes and many examples of this approach may be found in literature (among others, refer to the works by [4] and [5]). In all these cases, the laser and cross-correlation camera are synchronized based on a signal sent by an encoder mounted on the propeller shaft, so that acquisitions are made at the desired propeller phase angle. The two-propeller configuration under investigation in this work require a more advanced arrangement, because the phase-averaging process should be devised so as to take into account the relative phase angle between the two propellers. To this aim, a mixed hardware-software phase-locking scheme is designed and implemented. Laser emission and camera acquisitions are hardware-triggered by the downstream propeller encoder signal based on the desired propeller phase angle φ . The separation step of the latter may be appropriately chosen according to the symmetry of the blade geometry and the desired data resolution.

Each acquisition run consists of 6000 image pairs for which the downstream propeller angle φ is fixed at the desired value whereas the upstream angle θ features random values. This occurs because the propellers shafts are mechanically independent and there exists a slight difference between their rotation speeds. This mismatch in rotational speeds is thus exploited to attain a mostly homogeneous distribution of the upstream propeller phase angle over each acquisition. Since the encoder signal from the upstream propeller shaft is acquired over each single acquisition time window it is then possible to associate every image pair, and its related instantaneous flow velocity field, to a specific downstream and upstream propeller angle φ and θ respectively.

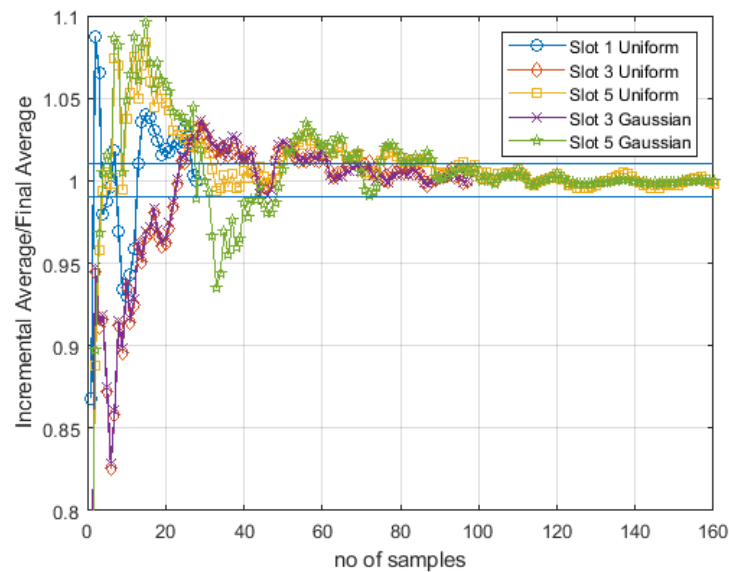


Figure 1: Convergence test on slot window size and weighing functions. Solid blue lines indicate $\pm 1\%$ range of the final value.

This approach thus implements a two-step hardware/software, i.e. on-line/off-line phase-locking scheme which allows sorting the data sets according to their phase angle pair φ , θ . This approach may provide a valuable insight into the relative effect of each propeller with respect to the other, which can be “frozen” in any desired position. We point out that since the aft propeller φ angle is determined a-priori it features discretized values whereas θ angle is random and its values lie in the range 0° - 360° with a resolution which depends directly on the forward shaft encoder resolution. This implies that the post-processing data sorting criterion should be carefully implemented so that a trade-off between the desired resolution of θ angle and corresponding size of the data sample is met. By following a similar approach to that presented in [6] we compared several data aggregation schemes, based on the window span and window weighing function. In Figure 1 it is shown the result of the convergence test carried out on the measured average of the axial component of velocity field in a selected flow location. Five combinations of window span and weighing functions for the upstream angle θ , namely 1° , 3° , 5° window span and uniform and Gaussian weighing functions are inspected, with the latter having variance of 1° . It appears that convergence within the range $\pm 1\%$ of the final value is reached already at 100 samples by the Gaussian weighing with a 5° slot size.

Once the weighing function is chosen based on a data convergence basis, a similar approach is followed to assess the most effective window overlap, which is strictly bound to the attained resolution of upstream phase angle θ . In Figure 2 five overlap levels, namely 0, 20, 40, 60 and 80% are compared, corresponding to a θ resolution of 5° , 4° , 3° , 2° and 1° respectively. The normalized axial component of velocity in a selected flow location is plotted against the upstream propeller phase angle. It is reported that at 1° resolution the velocity trend is faithfully measured without any artifacts. We point out that for convergence and resolution tests the flow was probed in a location which undergoes the passage of the propeller’s blade tip vortex in order to assess thoroughly the proposed scheme. Based on the assessment procedure described the chosen data reduction strategy for the general $\theta = x^\circ$ angle is therefore based on a Gaussian window weighing with a standard deviation of 1° , a window slot size of $x \pm 2.5^\circ$ and a window overlap corresponding to a resolution of 1° . A schematics showing this approach is provided in Figure 3.

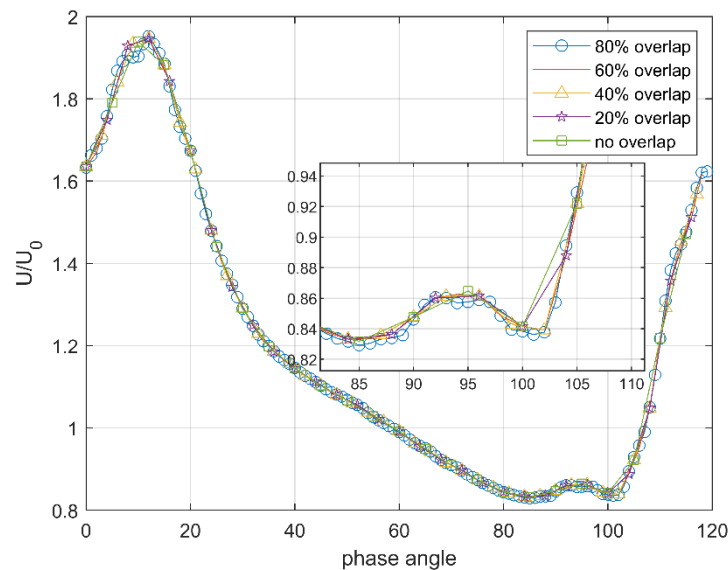


Figure 2: Slot window resolution test. Probe is located in a location undergoing the tip vortex passage.

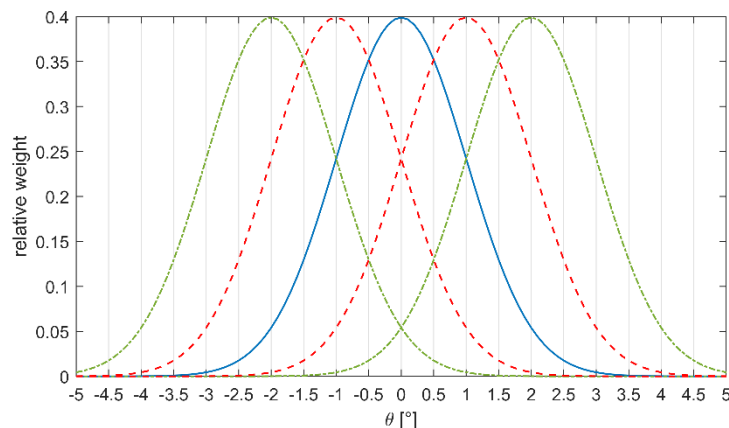


Figure 3: Schematics of chosen slot window and weighing scheme for the reference angle $\theta=0^\circ$. A Gaussian window with standard deviation 1° is used as a weighing function and samples in the range $\pm 2.5^\circ$ are considered. Neighbouring data (dotted red lines $\pm 1^\circ$, green lines $\pm 2^\circ$) are calculated at 1° degree resolution so that an 80% overlap is attained.

3. Results

It is well known and it has been shown by several Authors ([5,7] among others) that propeller blades generate a bound vortex and a trailing vortex system which is shed downstream. Due to the pressure difference between the back and the face of the propeller, a strong vortex is formed at the tip of each blade. As two propellers rotate in opposite direction, two systems of helical vortex tubes are formed, which give rise to complex interactions within the wake.

A systematic analysis of the wake structure, in terms of evolution of the wake flow field, is made possible by analyzing the mean axial component at selected θ , φ pairs. In Figure 4 the mean axial velocity field U made non-dimensional by free stream speed U_0 is shown for downstream propeller angle $\varphi=0^\circ, 40^\circ$ and 80° and upstream propeller's angle steps of $\theta=15^\circ$. Results are phase averaged according to the approach presented in the previous section.

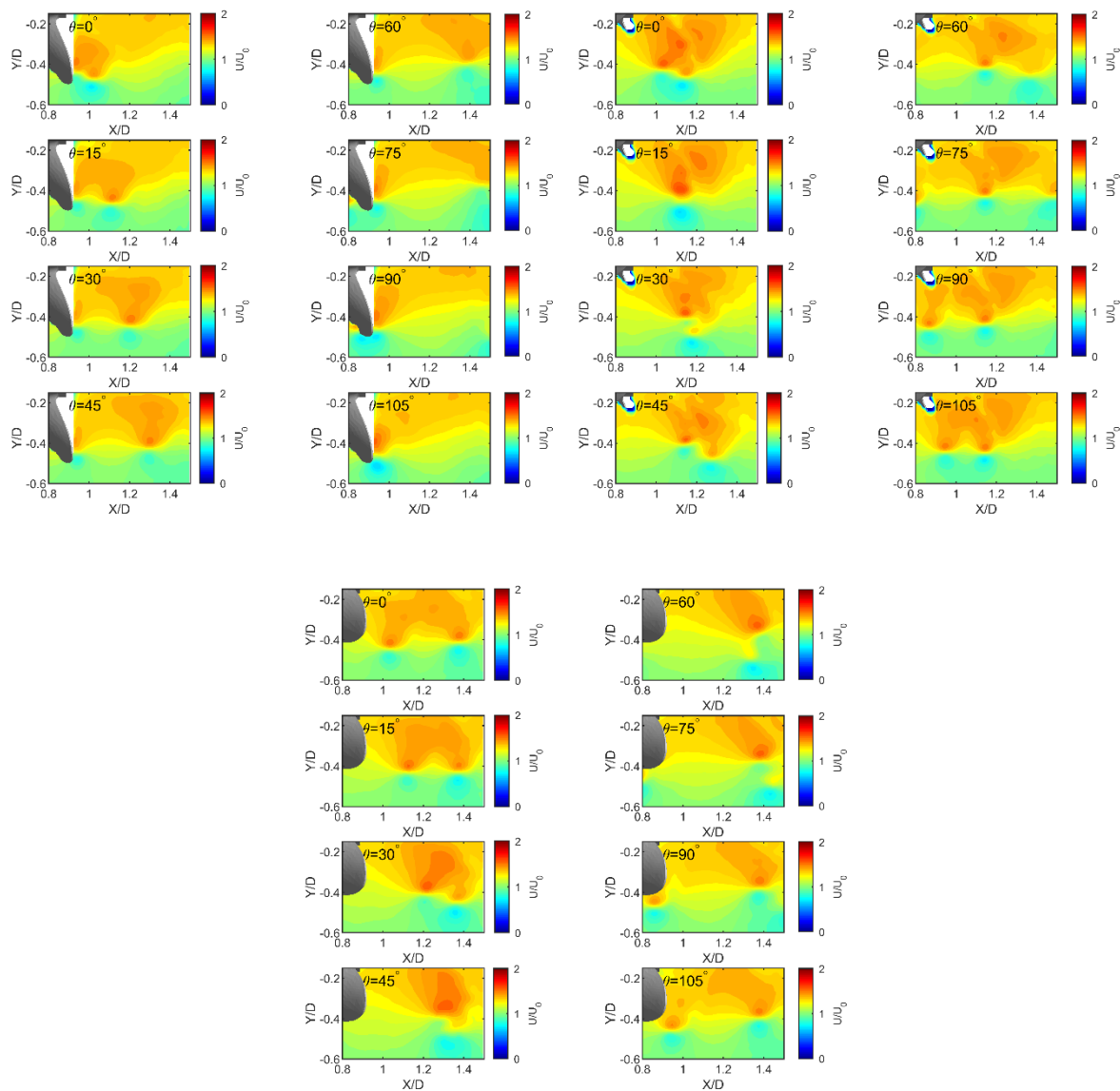


Figure 4: Phase-averaged normalized axial velocity component at upstream propeller steps of 15° . Downstream propeller phase angle $\phi=0^\circ$ (up left), $\phi=40^\circ$ (up right) and $\phi=80^\circ$ (bottom).

It appears that the viscous wake stemming from the roll-up of the boundary layers developing onto the propeller surfaces is linked to a local velocity defect which is noticeable at $\phi=40^\circ$ at $x/D \approx 1$ and at $\phi=80^\circ$ at $x/D \approx 1.4$. Some variations of these locations are reported dependent on the forward angle θ . In general, it is found that the aft propeller contributes to a strong flow acceleration in the wake, regardless of the relative position between propellers.

In Figure 5 the average spanwise vorticity ω , made non dimensional by D and U_0 , is shown for $\phi=0^\circ, 40^\circ$ and 80° and upstream propeller's angle steps of $\theta=15^\circ$. As expected, the trailing vorticity shed by the forward propeller blade's trailing edge is characterized by two layers of opposite sign. This feature is due to the boundary layers developing onto the blade surfaces.

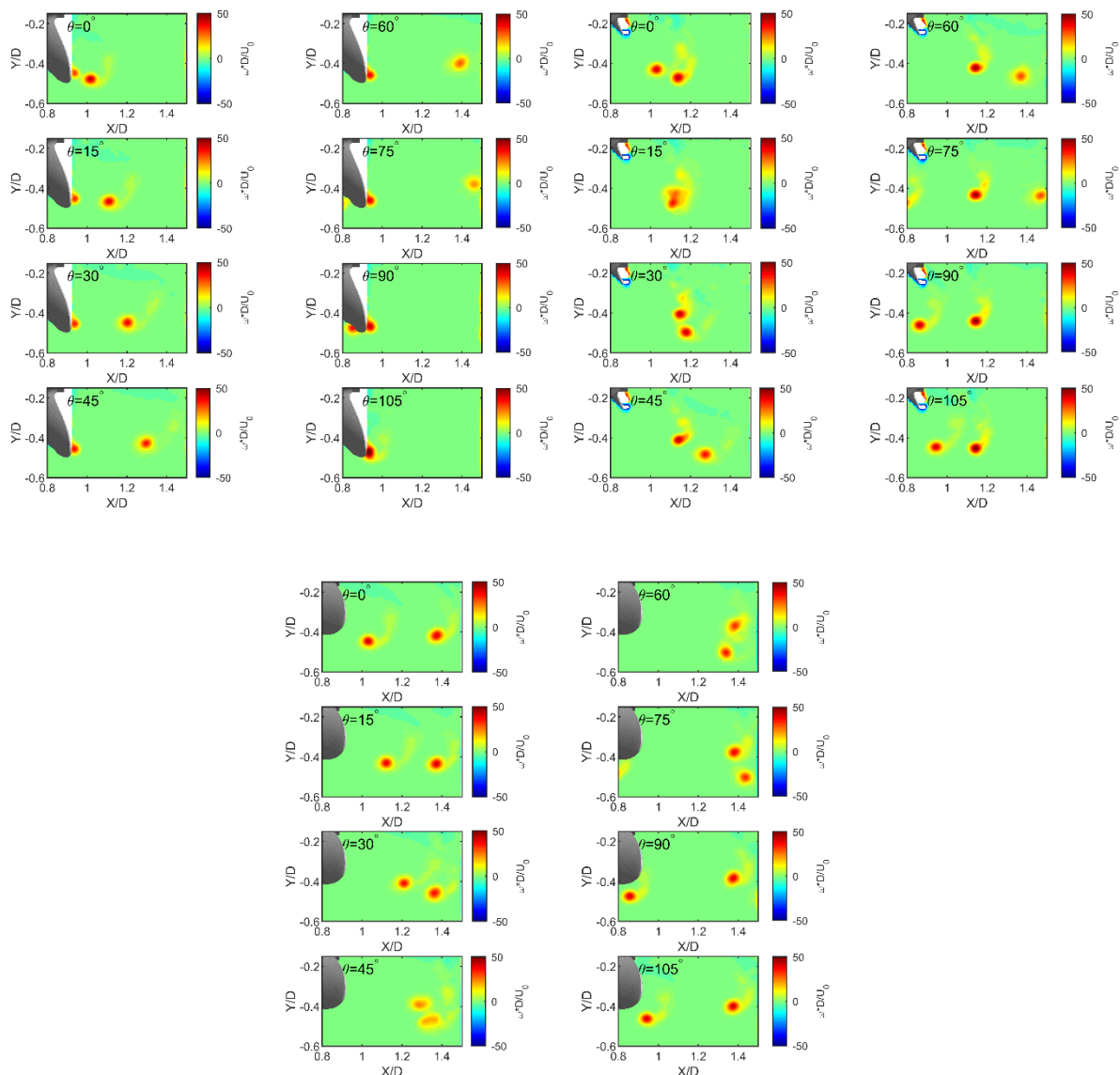


Figure 5: Phase-averaged normalized spanwise vorticity at upstream propeller steps of 15° . Downstream propeller phase angle $\varphi=0^\circ$ (up left), $\varphi=40^\circ$ (up right) and $\varphi=80^\circ$ (bottom).

The evolution of the spanwise vorticity field is markedly dependent on the relative phase angle between the two propellers. For $\varphi=0^\circ$, the tip vortex from the upstream propellers is convected downstream relatively undisturbed, except for the phase angles $90^\circ < \theta < 120^\circ$ for which it interacts with the downstream propeller's tip vortex. For $\varphi=40^\circ$, 80° a strong interplay between the tip vortex and trailing vorticity from the two propellers is reported. As the tip vortices are in proximity to each other, break-up and merge processes take place, as noticeable for $\varphi=40^\circ$, $\theta=15^\circ$. This phenomenon is weaker for $\varphi=80^\circ$, as the tip vortices undergo deformation within the acquisition plane but do not apparently merge. It is worthwhile to point out that these events are supposedly associated to local energy exchange and consequently could be associated to undesirable effects such as increased vibrations and radiated noise.

4. Conclusions

In this work, a mixed hardware/software (on-line/off-line) phase locking scheme is presented which allows investigation of phenomena characterized by more than one periodic source. This approach is followed for the investigation of the wake of a contra-rotating propeller system and is implemented in a Planar Particle Image Velocimetry system. Assessment of the most effective data sorting strategy is carried out in terms of slot size and weighing window. Sample results show that strong interactions take place between the trailing vorticity systems stemming from each propeller. Their extent is strongly dependent on the propellers relative angle.

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