A DIS-based Air Cavity Concept for Planing Hull

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Abstract. Reducing fuel consumption and carbon emissions are two of the main concerns of the maritime industry. Among the available energy-saving devices or solutions, one of the most promising is air lubrication, which has been extensively studied in the last decades, especially for drag reduction on displacement hulls.

Compared to displacement hulls, planing and semi-planing hulls have different hydrodynamic behaviour since the resistance and running attitudes are significantly influenced by the hydrodynamic component of pressure, which can influence the effectiveness of the air lubrication solution.

This study proposes an air lubrication solution for a planing workboat that combines the airflow injection with an air cavity provided by a DIS (Double Interceptor System) implementation.

The results of experimental and CFD simulations campaign with natural and forced airflow injection combined with a cavity generated by DIS are presented. The drag resistance improvement and the airflow details have been analyzed by the use of a systematic variation in the airflow rate.

Keywords. planing hull, air lubrication, air cavity, Double Interceptor System (DIS)

1. Introduction

A method for reducing the resistance of a ship and, hence, its fuel consumption is the Air Lubrication (AL) technology. It consists of the introduction of a gas (generally air) beneath the hull through flushing holes, in order to modify the boundary layer.

The resistance reduction mechanisms depend on the methodology used. In the case of the injection of a discrete quantity of bubbles, there is a variation of the fluid average density and the modification of the momentum transport in the boundary layer, instead in the case of continuous feeding of air, the established air layer reduces the wetted surface. Ceccio *et al*. [1] made a clear description of the physics of the air inflation mechanism highlighting the important role of the friction resistance reduction.

A historical overview and an analysis of the initial applications of the AL for planing crafts were reported by Latorre [2]. It is possible to distinguish different techniques for AL: Bubble Drag Reduction (BDR, or MBDR Micro-Bubble Drag Reduction), Air Layer

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Drag Reduction (ALDR), Partial Cavity Drag Reduction (PCDR, sometimes called Air Cavity).

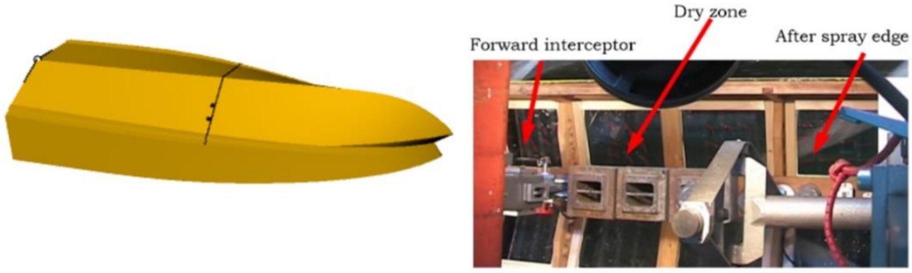
In BDR, bubbles with a very small diameter (about 0.1 mm) are injected underneath the hull. First pioneer experiments on the use of bubbles were conducted by McCormick and Bhattacharyya [3] on a fully submerged body, wrapped by bubbles created by electrolysis. It was seen that the bubbles altered the laminar and turbulent boundary layer and this led to a significant drag reduction. Years later Kodama *et al*. [4] obtained a skin friction reduction of about 40% on two flat plates with different porous configurations, using a circulating water tunnel. It was found to have a greater drag reduction at lower speeds and large airflow rates.

In ALDR, a certain quantity of air is introduced under the hull and it coalesces into a continuous (or partially continuous) layer that separates the solid surface from the water flow. If the air flux is sufficient to achieve a stabilized layer, the air tends to cover a large part of the hull bottom with a significant reduction of the wetted surface. Elbing *et al*. [5] performed a series of experiences for high Reynolds at the W. B. Morgan Large Cavitation Channel on various flat plates. Different configurations of flat plates with flushing injection holes were towed at 15.3 m/s. The results showed an 80% drag reduction once the air layer is stabilized. It was observed that the airflow rate required to achieve the ALDR was proportional to the square of the free-stream speed. Later, the experiences of Jang *et al.* [6] consolidated the potential benefit of the ALDR for ships and pointed out the need for a uniformly spreading of gas in order to maintain the beneficial effect on resistance. Park and Lee [7], obtained a drag reduction of up to 18% during towing tank tests on a tanker model ship and pointed out the effectiveness of dispersed gas injection (instead of a single injection).

Adopting the Air Cavity method, the air is introduced into an artificial cavity created under the bottom, generally aft of a step or an abrupt discontinuity of the hull. The air cavity has been studied, among others, by Gockay *et al*. [8] through resistance tests of two high-speed hull forms; a conventional prismatic planing hull and a second one with a recess tested with two different airflow rates and without air. For the air cavity hull, a reduction of resistance of 20% was measured, but no significant changes were observed for different air supply rates, although a constant airflow is necessary to replenish air losses. The lower viscous resistance by reducing wetted surfaces was indicated as the main reason for the reduced resistance. Recently, Matveev [9] studied the behaviour of a wide-beam air cavity hull in waves by means of CFD analysis. Key issues are the sustaining of air lubrication in rough seas, where the effectiveness of these methods decreases.

2. The Double Interception System

Interceptors are high-lift devices, applied to the transom of planing and semi-planing hulls, acting substantially as trim controllers. The main limitation of this device is the extreme trim correction at high speeds. To overcome this effectiveness reduction, a *Double Interceptors System (DIS)* solution has been proposed by De Luca and Pensa [10]. This solution consists of two interceptors, as shown in Figure 1(a), one, as usual, located at the transom and the other one at a certain distance from the transom.



(a) (b)

Figure 1. (a) Hull equipped with DIS system, (b) DIS effect of the wetted surface distribution (from De Luca and Pensa [10]).

The function of the DIS is to establish a forward zone of overpressure to increase lift and counteract trim reduction due to the stern interceptor. Furthermore, as clearly depicted in Figure 1(b), the DIS, thanks to the induced flow detachment, ensures a further improvement in performance by significantly reducing the wetted surface.

However, a similar reduction of wetted surface can be detected even on the stepped hulls or other air-injection-based solutions but with two important differences. Firstly, the dry zone is induced by the interceptor flow deflection instead of the hull surface discontinuity. Secondly, only the interceptor can generate a high-pressure area upstream of the flow detachment. These differences lead to the high lift effect due to differences in pressure distributions and dynamic trim angles.

The effectiveness of the DIS depends on speed and hull form. Indeed, for some specific geometries and speeds, the DIS has led to a reduction in effective power by up to 20%, De Luca and Pensa [10]. However, so far, the fields of application of this device are not so well-defined and well-investigated. In fact, the DIS can trigger dynamic instability phenomena at the highest speeds (De Luca and Pensa [11]), and ventilation problems can arise on specific hull geometries, in particular, with a low slenderness ratio and/or in heavy-loaded conditions.

3. Numerical and experimental program

The main goal of the study is to investigate the feasibility of airflow injection as an improvement of the DIS effectiveness even for hull forms or speed ranges where the DIS has shown to be not effective. For this purpose, the C1505 model was chosen, for which the experiments in the towing tank with and without DIS have highlighted serious performance issues. The height of the interceptors is 2 mm. The stern interceptor width is 0.5·BWL.

The main dimensions and coefficients of the model are shown in Table 1. Figure 1(a) shows a perspective view of the model.

Table 1. C1505 Model, hull details.

LWL (m)	BWL (m)	T (m)	LCB (m)	TCB (m)	VCB (m)	∇ (m^3)
2.313	0.909	0.157	0.867	0.000	0.093	0.110
SW (m2)	**AW (m2)**	**LCF (m2)**	**CB**	**L/∇1/3**	**L/B**	**B/T**
1.747	1.474	0.884	0.335	4.823	2.546	5.804

The experimental campaign showed that, for this model, the main reason for the DIS's reduced effectiveness was due to the insufficient ventilation of the dry hull area. Therefore, to avoid the subsequent low pressures, forced ventilation (through air injection) could be assumed as an adequate solution.

Consistently, a numerical-experimental study was planned to evaluate the resistance of the model depending on the flow rate of injected air.

So far, the study has been articulated in three different stages:

- Towing tank tests of the model with and without DIS, with natural and forced airflow;
- CFD resistance simulations using the same towing tank sailing conditions to validate the numerical setup;
- CFD resistance simulations with different airflow rates, investigating the optimal range of rates.

For the present analysis, the speed range investigated was F_r = 0.97 - 1.46 ($F_{r\nabla}$ = 0.67 - 1.01). To identify the airflow rates, the natural one (Q_n) was estimated through a simulation with opened ducts behind the forward interceptor. The natural airflow is obtained by means of four open pipes (two per side) with a diameter of 20 mm each, located at 184 mm and 269 mm from the centerline, and 1080 mm from the transom stern. Then, simulations were performed with forced airflow rates equal to $2Q_n$ and $5Q_n$, a complete overview of the different airflows applied is available in Figure 3(e). All the tested cases are summarized in Table 2.

Table 2. Details of tested and simulated C1505 hull configurations.

Serie	Description
“Serie 15”	Experimental tests, DIS with natural flow
“No Air”	CFD simulations, DIS, no air, no pipes
“Natural Flow”	CFD simulations, DIS, natural airflow (Qn)
“×2 Natural Flow”	CFD simulations, DIS, forced airflow (2Qn)
“×5 Natural Flow”	CFD simulations, DIS, forced airflow (5Qn)

4. Numerical setup

The URANS simulations were conducted using the commercial CFD code Siemens PLM Star CCM+. A Semi- Implicit Method for Pressure-Linked Equations (SIMPLE) to conjugate pressure and velocity field has been used to find the field of all hydrodynamic unknown quantities, and an Algebraic Multi-Grid (AMG) solver was used to accelerate the convergence of the solution. A segregated flow solver approach has been used for all simulations. The free surface has been modelled with the two-phase VOF approach with a High-Resolution Interface Capturing (HRIC) scheme based on the Compressive Interface Capturing Scheme for Arbitrary Mesh (CICSAM).

The wall treatment utilized for all simulations is the *All Wall y+*. This is a hybrid approach that emulates the *high y+* wall treatment for coarse meshes (for y+>30), and the *low y+* wall treatment for fine meshes (for *y*+≈1). Furthermore, this approach gives a reasonable answer for meshes of intermediate resolution (for *y*+ in the buffer layer), as depicted in Siemens PLM Star-CCM+ v 2021.2 User’s Guide [12].

The URANS simulations were carried out using the Overset/Chimera grid to follow the hull motions. The linear interpolation method has been applied to establish the connectivity between the background and the overset region. More details about this approach are available, for instance, in De Luca *et al.* [13], and Begovic *et al.* [14].

The boundary conditions applied and the computational domain dimensions are shown in Figure 2. These dimensions comply with the ITTC guidelines [15] and even the time step size is determined through the formula suggested by the ITTC guidelines [15].

The forced airflow rate is obtained by setting a given value to the mass flow outlet boundary.

The natural mass flow "Qn" has been measured at the mass flow outlets, without any artificial mass flow condition being imposed. The flow outlets under the hull were open to the atmospheric pressure, modeling the geometry of the actual pipes.

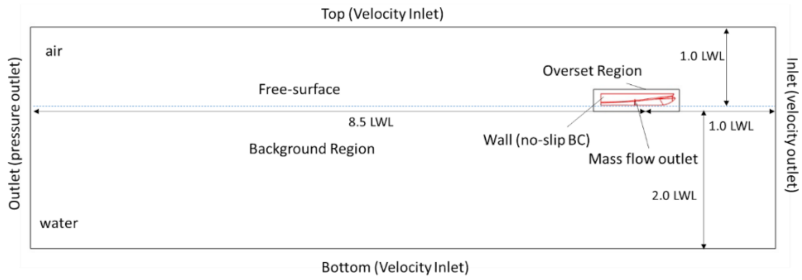


Figure 2. Computational domain and its boundary conditions.

5. Experimental procedure

The experimental tests were carried out in the towing tank laboratory (LEIN) of DII (*Dipartimento di Ingegneria Industriale*) at the *Università degli Studi di Napoli "Federico II"*. The towing point is placed on the LCG at waterline level. The towing force was kept constantly horizontal. The model was free to rise and pitch. In accordance with the reference ship, the defined center of gravity leads to a static trim of 0.6 deg forward. No turbulence stimulators were applied, due to the high Reynolds numbers reached during the tests (Re > 1.0×10^7).

6. Results

The DIS, as exposed in the previous paragraphs, represents a high-lift device that generates an overpressure at the stern as well as forward using two separate interceptors. The forward interceptor counterbalances the stern interceptor effects, more specifically, it counterbalances its induced trim reduction. The DIS has been applied on the C1505 hull, for which it did not show the performance improvements obtained on hulls with higher slenderness ratios.

The comparison between the experimental results and CFD simulations has been performed for the hull configuration equipped with DIS and the two pipes with natural ventilation ("Serie 15") and is available in Figure 3(c). The comparison shows a discrepancy error for the hull resistance in the range of -0.9% / +2.5% and for the trim angle between -2.0% and +10.0%.

All the simulated hull configurations are compared in Figure 3 and the relevant values are plotted, specifically: in Figure 3(a) the hull resistance, in Figure 3(b) the trim angles, in Figure 3(d) the wetted surfaces, and in Figure 3(e) the enforced airflow rates.

Looking at Figure 3(a), the effect of DIS is significantly improved by the action of the air supplied: the greater airflow rate, the lower the hull resistance. The hull resistance with DIS is decreased by 3.0% to 7.9% when natural ventilation (Q_n) occurs, the resistance reduction is driven by the reduction of the wetted surface (Figure 3(d)).

The "5Qn" case is consistent with the performance improvement trend observed in the natural ventilation case, showing hull resistance reduction up to 16.0% compared with the "No air" case. Also this improvement is led by the wetted surface reduction. Moreover, it is noteworthy to observe that the airflow establishes a steady air layer along the hull bottom with a few vortex structures developments compared with the other cases, as shown in Figure 4(d).

On the contrary, the configuration with DIS and 2Qn ventilation seems to be not in line with this trend mainly at the highest speed. Indeed, this configuration is not able to guarantee a performance improvement when compared with the natural ventilation case. The explanation of this behaviour could be found by observing the following points:

- The airflow interacts with the momentum of the fluid mixture (water and air) acting on the stern interceptor, eventually changing the stern interceptor's effectiveness (see VOF views in Figures 4 (c) and (d)).
- The magnitude and center of application of the pressure force on the dry area act on the hull, influencing its trim angle (Figure 3 (b)) and wetted surface (Figure 3 (d)). Indeed, the increase of the wetted surface is led by the trim angle reduction that increases specifically the forward wetted surface area (forward the first interceptor).
- Airflow instabilities, visible comparing the vectorial views in Figures 4(c) and (d), seem to decrease with increasing airflow rate.

7. Conclusions and Future Works

This study proposes an air lubrication solution for a planing workboat combining airflow injection with an air cavity solution provided by the DIS. The investigation has been carried out by means of experimental tests and CFD simulations and the effect on the hull performance of the airflow was examined by inducing a systematic variation in the airflow rate.

The results highlighted how the air injection can significantly improve the planing hull performance in the entire range of speeds of interest. The hull drag reduction is up to 16.0% compared with the case of the hull equipped with DIS only. Furthermore, the airflow injection seems to be a viable solution even to improve and extend the benefit and effectiveness of the DIS solution.

The analysis has shown a non-fully linear trend between performance improvement and increasing airflow rates.This leads to think that some mutual interaction exists between the interceptors (mainly the stern interceptor of DIS) and the airflow that needs to be further investigated with detailed analysis. Furthermore, in order to assess the real potentiality of the proposed solution as an energy-saving device, a detailed analysis of the power requirements of the airflow injection system will be carried out in order to estimate the total energy required by the proposed solution.

Acknowledgements

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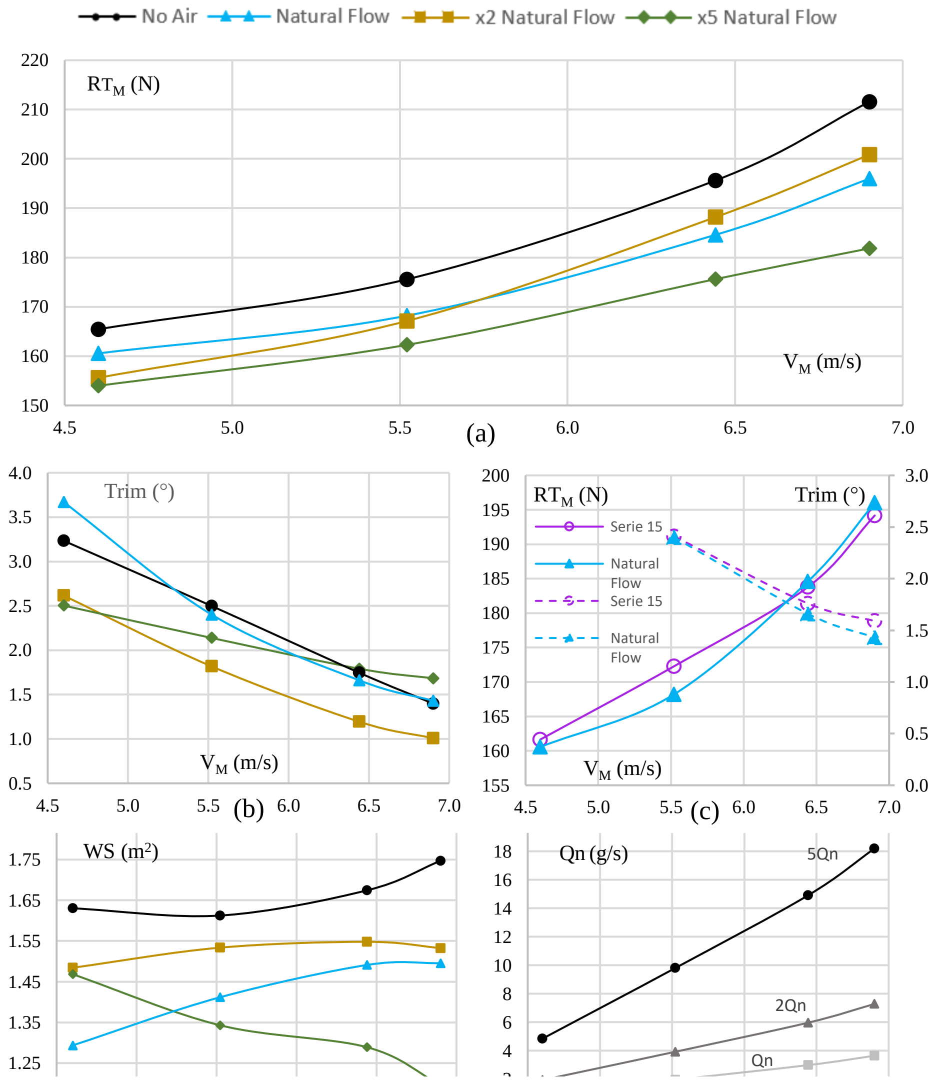

Figure 3. Results of experimental tests and CFD simulations. (a) Hull resistance, (b) Trim angles, (c) Resistance and trim angle comparison between experimental and CFD results for hull equipped with DIS and with natural ventilation, (d) Wetted Surfaces, (e) Airflow rates

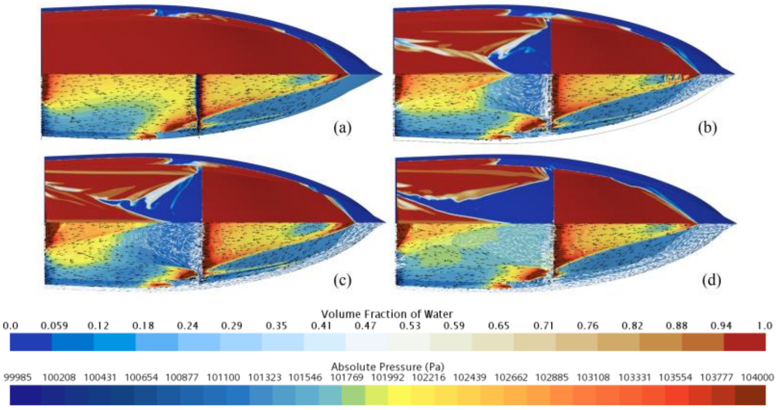

Figure 4. Volume of Fluid (VOF) visualization (Upper parts), Air (Blue) - Red (Water) and Total pressure (Down parts) with the vectorial representation of the velocities of the air and water components, for the different hull configurations simulated: (a) DIS no air, (b) DIS with Qn airflow rate, (c) DIS with 2Qn airflow rate, (d) DIS with 5Qn airflow rate, all the cases at speed 6.91 m/s.

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