An innovative concept for Inland Waterway Vessels

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Abstract. The European Inland Waterway Transport (IWT) is a viable and effective alternative to road and rail transport of persons and goods on the European network. Currently, the IWT is less exploited than the 'traditional' transport despite the European inland waterway network spans more than 29000 km and includes over 400 important ports and terminals. The design of inland waterway vessel is heavily affected by the environmental constraints and the Rule framework. About the latter, in the last few years several organizations played an important role in the definition of the Rule framework in Europe: the United Nations Economic Commission for Europe (UNECE), the European Union and various local area commissions. The tendency of international regulations is to make inland waterway decarbonised by reducing pollutant emissions through ships with zero-emission propulsion. Moreover, the design is also affected by environmental constraints like width and depth of the canals, air draft, etc. In this paper, a 'new concept' for inland waterway vessel, which considers the modern national and international regulations and the environmental constraints, has been defined. A case study and the results obtained have been analysed.

Keywords. Sustainable navigation, Inland navigation, Inland waterway transport, Air cavity, Innovative propulsors.

1. Introduction

In a global context, where environment safety and pollution reduction is one of the most important cores for modern society, the Internal Waterway Transport (IWT) represents an attractive alternative or addition to road and rail transport on European corridors [1]. In fact, IWT is suitable for almost all kind of goods (solids or liquids), moreover, being statistically one of the most safe transportation mode, it can be also indicated for hazardous goods. For this purpose, it is of primary importance to study which technologies can be adopted to further reduce environmental impact of IWT. In fact, with the new restrictions on emissions imposed on road transport system, IWT may result, for certain routes, cargo types and vessel sizes, more pollutant than road transport in terms of emissions per tonne-kilometre. This is mainly due to the fact that

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the modern emission regulations are not applied on old IWT vessels, but only on new constructions.

To improve the situation, several studies have been already successfully performed and applied. They concern the use of alternative fuel types, like Liquefied Natural Gas (LNG) [2,3], or the adoption of hybrid-electric power systems [4]. Inland waterways can be also used for passenger transportation. In this case, innovative and sustainable solutions can be applied for areas close to the coast [5], lagoons [6] or internal rivers and lakes [7], where pollution limitations are of extreme importance.

Through this paper, the idea of the conversion of an old unit to reduce pollution has been discarded, and consequently a new design has been studied, taking into account not only the fuel type and power management system, but also the ship in its totality. As a matter of fact, for the transportation of goods in the North-Adriatic area, including inland and coastal service, a new gas-fuelled vessel has been designed with hull forms modified in order to adopt an air-cavity system for drag reduction, and with innovative propulsors. In this work an overview of the design along with the description of the main innovations installed on board will be given.

2. Working Environment

Conventionally a waterway is defined as each kind of navigable body of water. That means a first distinction should be made between maritime shipping routes and waterways used by inland water crafts.

Maritime shipping routes cross oceans and seas, and some lakes, where navigability is assumed, and no engineering is required, except to provide the draught for deep-sea shipping to approach seaports (channels), or to provide a shortcut across an isthmus. Usually dredged channels access to seaports are not considered as waterways, however once a port is located inland, the access can be described as maritime waterway, as for the Rein, Seine, Loire or Elbe estuary. The definition of inland waterway is primarily referred to navigable rivers and channels designed to be used by inland waterway crafts only, which are implicitly smaller than conventional seagoing ships.

Since 1953 the European Conference of Ministers of Transport, established a classification of internal navigable waterways as a function of the maximum vessel class that can travel trough the waterway itself. The classification is based considering the case of a single inland vessel or of a convoy. In any case, the classification is made with regard to vessel length, breadth, draught and tonnage. Another important parameter to consider is the minimum height under the bridges, which is automatically referred to the maximum height of the vessel superstructure. In such a manner the waterways are checked in order to fit specific vessel classes. This means that they take the rank of the maximum vessel class they are able to accommodate with sufficient safety. Merchant vessels for inland navigation are divided in classes from *I* to *VII*, plus additional subclasses related to the specific configuration of barge convoys, and the waterways are directly identified with the same class notation. With the specific aim to focus the attention on the sustainability of inland navigation in Italy, particular attention should be given to the status of the internal waterways in this country. Here inland navigation is mostly developed in two areas, one located in the North Adriatic, including Venice and Marano lagoons, the other one in the Po river basin. Of particular interest for touristic reason is also the inland navigation in the main North Italian lakes

(Garda, Como, Maggiore and Iseo). However, the waterway system is not suitable to connect lakes with the rest of the navigable areas.

The current status of the Italian inland waterways, will allow a vessel to reach at most Mantova from the North Adriatic with at most a *IV* class vessel. It is planned to extend certain channels around Ravenna up to *V* class in such a way to be able to sustain a class *V* navigation in the first part of the Po river.

It must be noted that a navigation in this kind of waterway cannot be considered as purely internal, in fact a vessel that wants to connect the two internal areas must cross part of the North Adriatic, crossing the path between internal and coastal navigation. This means that the vessel should be properly designed to consider this peculiar aspect.

3. Hull form development and optimisation

The hull has been designed for a channel class *V* navigation and for coastal navigation. The main dimensions are limited by the waterway class notation. The maximum length, breadth and draught have been fixed to 110.0 m, 11.4 m and 2.8 m, respectively. The ship is mainly designed for the transport of containers or coils.

The final draught has stemmed by a process of optimisation concerning resistance and displacement, balancing hull forms to reduce dynamic trim in shallow water and designing stern forms for arranging vertical axis cycloidal propulsors.

The optimisation of the hull was carried out through a CFD analysis with the software STARCCM+, starting from the forms of a conventional barge as shown in Figure 1.

Bow and stern forms were modified step by step smoothing waterlines and reducing the rise of bow and stern. Figure 2 shows the final hull forms, which allows a total resistance reduction of about 10% with respect to the initial hull.

The new bow shape gives sufficient buoyancy during navigation at full speed in deep water, as well as a wave pattern height reduced in comparison with the initial hull. The free surface elevation of the two hulls is shown in Figure 3.

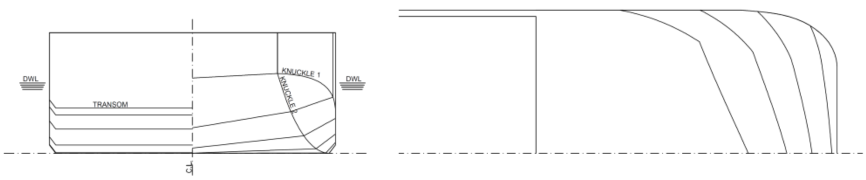

Figure 1. Initial hull.

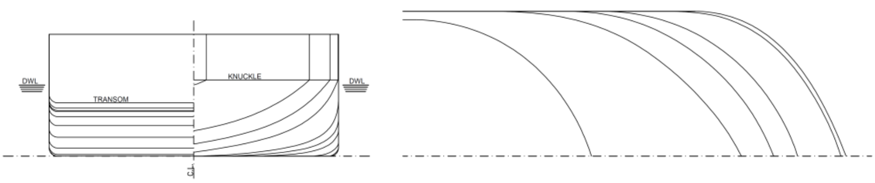

Figure 2. Optimized hull.

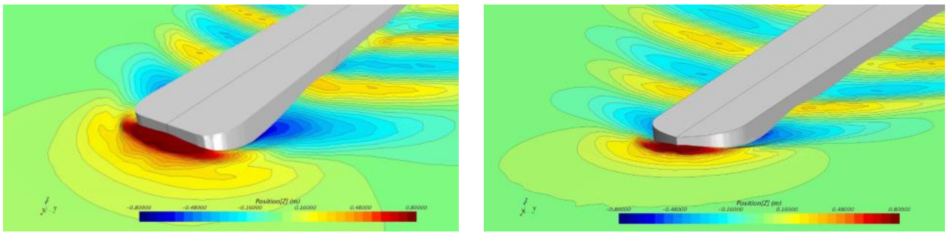

Figure 3. Free surface elevation: initial hull vs optimized hull.

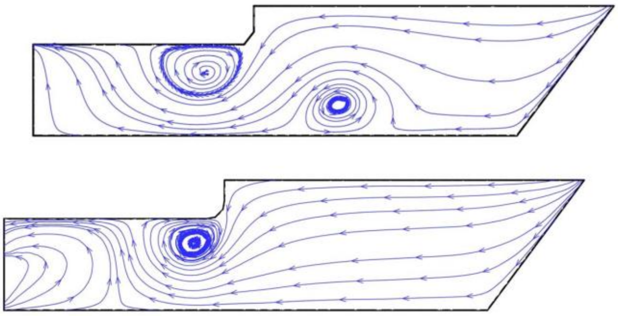

Figure 4. Streamlines in channel transverse section near propulsor axis: initial hull vs optimized hull.

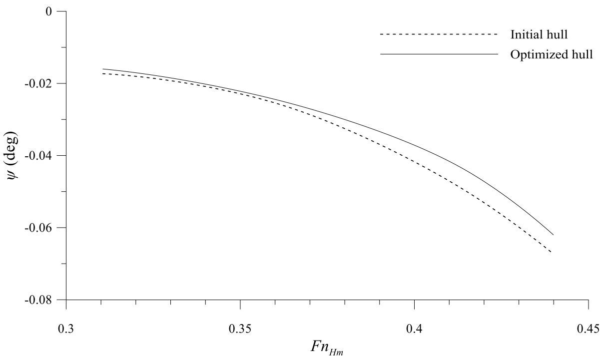

Figure 5. Dynamic trim in channel (positive trim by stern).

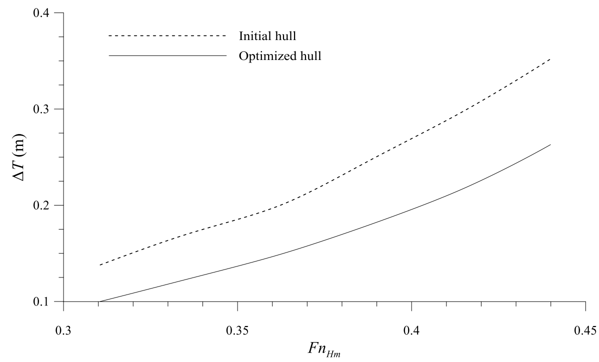

Figure 6. Dynamic sinkage in channel.

In Figure 4 a channel transverse section is shown at river depth (H) - ship draught (T) ratio equal to 1.6, which corresponds to the design condition. In the optimised hull there are less vortices produced from the interaction between the hull and the channel walls, moreover the flow from bow to stern is more steady than the original hull.

In the process of optimisation, particular attention has been given to dynamic trim, which plays a fundamental role in shallow water navigation. Furthermore, in order to avoid grounding in dynamic conditions (Figure 5 and 6), hull forms that allow to reduce trim and sinkage have been properly designed.

4. Air Cavity System and model test campaign

To further improve resistance performances and reduce environmental impact, the ship has been fitted with an Air Cavity System (ACS). Such a system consists in a recess obtained on the ship bottom, which is filled with air bubbles through dedicated compressors. The system is particularly suitable for ships with extended flat bottom, which sails in calm water, as the case of river navigation.

In order to study the ship with and without the ACS installed, a model tests campaign were performed at Krylov State Research Centre in St. Petersburg, measuring the resistance performances in deep water, shallow water and in channel with a 1:15-scale model.

Model tests were carried out at different H/T ratios (channel depth / ship draught) for a fixed hydraulic radius. The total resistance in channel R_T at H/T = 1.6 (design condition) versus average-depth Froude number Fn_{Hm} is shown in Figure 7 with reference to the model with and without ACS. As can be noted, the resistance of the model with ACS is up to 20% lower than that of the base model.

From Figure 7, it is clear that when the ship speed exceeds the channel critical speed (V_{CR}), the resistance dramatically increases. This is caused by both the wave making resistance (due to a change of the wave pattern) and the viscous resistance (due to the return current). The phenomenon is shown in Figure 8 with the backflow wave that rises on stern. In river navigation the speed limit V_{CR} might not be exceeded in order to avoid deleterious loss of maneuverability and course stability, as well as erosion of river flanks and wave impact on shore facilities.

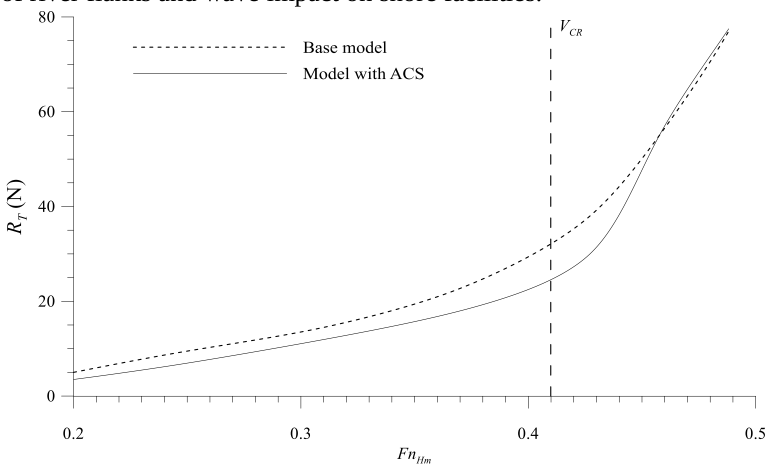

Figure 7. Total resistance in channel for model with and without ACS at H/T=1.6.

Figure 8. Resistance test in channel above the critical speed V_{CR}.

5. Bivortix propulsion system

In the present case study, in addition to the optimisation work done on the hull forms, to the arrangement of an ACS and to the adoption of LNG fuel for the propulsion, a vertical axis cycloidal propeller, named Bivortix, has been considered.

Bivortix represents a new propulsion system, internationally patented and licensed by Tergeste Power and Propulsion Company. It derives from Kirsten-Boeing propeller and it is based on two coaxial impellers with vertical moving blades [8]. The direction of the thrust is obtained through a synchronized orientation of the blades of both the impellers without acting on the angular velocity and on the direction of rotation of the two impellers.

In shallow water, rivers and lagoon areas, the presence of various obstacles along the route require a propulsion system with great manoeuvring capabilities. The new propulsion system Bivortix can be considered a valid alternative to the traditional rudder-screw propeller system, allowing at the same time both the propulsion and the steering of the ship with a single mechanical system.

During previous experiments, this system has also shown excellent low speed thrust (over 300 N/kW) [9], and, by considering that the thrust direction can be quickly oriented by 360°, the system is particularly suitable for manoeuvres in congested areas.

The shallow water typical of inland waterways often do not allow to adopt large conventional propeller, and consequently the propellers have smaller diameters and high rotation speed regimes. Alternatively, ducted propeller, which is more efficient and able to direct the thrust within a certain angle range, can be used, but requires adequate hull forms, which in general subtract internal payload space.

The Bivortix propeller can also work in shallow waters: the relatively short blades are indeed adjustable according to the power required and the type of navigation to be performed. It does not need any particular hull shapes: its optimal installation is on flat-bottomed hulls, and the internal space required is very small. Furthermore, the absence of propeller shafts allows a space recovery and low installation costs.

The traditional vertical axis propellers show good manoeuvring abilities and good thrust, but reduced efficiencies with respect to the conventional screw propellers. Moreover, a traditional vertical axis propeller produces an asymmetric thrust, which forces designers to place two counter-rotating propellers side by side in order to eliminate such an asymmetry. Bivortix, instead, being already a contro-rotating system, does not present such a trouble, and consequently there is a higher efficiency and then a lower fuel consumption.

Different parameters may affect the efficiency of the Bivortix system: the geometrical blade features, the number of blades contained in each rotor, the installation position on the hull, the propeller revolutions, the ship speed and the engine power. To investigate on these parameters many experimental test have been carried out.

The preliminary open-water tests conduct on the first prototype BVX-1, which took place in the Vienna Model Basin Institute, showed excellent results in terms of thrust coefficient and efficiency [8].

In a second experiment campaign (BVX-2 model), in which many tests were carried out at sea, some of the characteristic parameters were optimized: a greater thrust and a reduced incidence of cavitation was obtained, meanwhile a better understanding of the relationship between efficiency and hull geometry was attained [9].

Based on these experiences, a further larger model (BVX-3) has been designed and built, in order to predict the real size of the propeller to be installed on the ship with the Air Cavity System. The BVX-3 prototype is 850 mm wide, mounts blades 450 mm long, which have a specific NACA profile capable to reduce the drag coefficient and to maintain a high coefficient lift with the aim of obtaining a higher thrust even at reduced rotational speed. Test experiments are scheduled in April 2018 to be performed at the Krylov State Research Center in St. Petersburg.

6. Conclusion

The idea to improve the greenness of the vessel, through the entire design process, has lead to the design of a modern and innovative concept of inland ship.

The design choices related to the adoption of an Air Cavity System and of a modern vertical propulsor, have influenced the optimisation process of the hull form, determining a shape suitable to sail in different environments (shallow and deep water) at different speeds and hydrodynamic regimes, without loosing to much efficiency as highlighted also by model tests.

The integration between a well optimized hull form able to allocate an innovative propulsor and the a gas-fuelled propulsion plant has given a set of benefits for the new unit. Besides the pollution reduction, also fuel consumption has been lowered, resulting in a drastic reduction of the operational costs.

The research work performed is an example of how the synergy between different parties can contribute to attain the design of a successful product.

Acknowledgements

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