Hydrofoil Technology: Current Applications and Future Developments for Sustainable Boating

Domenico Speranza[1] , Stefano Papa[2] , Claudio Pensa[3] ,
and Romolo Di Bernardo[1(✉)]

[1] University of Cassino and Southern Lazio, 03043 Cassino, Italy
romolo.dibernardo@unicas.it
[2] Università degli Studi Niccolò Cusano, 00166 Rome, Italy
[3] University of Naples Federico II, 80125 Naples, Italy

Abstract. Submerged lifting surfaces technology, born in the early 1900s, allows boats to lift the hull above the water and, in some cases, halves the resistance compared to dislocated and planning boats.

This paper illustrates the state-of-the-art on hydrofoil technology, highlighting the fundamental aspects of the study of submerged wings and focusing on the problems that this technology presents, evaluating the solutions currently used to optimize its work.

Key aspects of hydrofoil design are addressed, such as the choice of geometric configurations and two-dimensional profiles suitable for each type of mission. This results in addressing issues associated with cavitation and ventilation and emphasizing structural solutions that reduce these phenomena, thus improving hydrofoil efficiency.

The study analyses and discusses the problems of wing systems used in existing applications, with the aim of developing a sustainable transport technology compatible with ecological propulsions such as hydrogen and electric.

Keywords: hydrofoil · sustainable · hydrodynamics · green

1 Introduction

Hydrofoil technology was born in the early 1900s thanks to Eng. Enrico Forlanini, who installed load-bearing surfaces under the hull of the hydroplanes, very similar to aircraft wings, which allowed him to completely lift the hull out of the water. Research into hydrofoils, particularly in the mid-20th century, was primarily carried out in the military and only after some years, during the 60s, this technology was also used in the commercial ship [1], thus the first hydrofoils ferries with tandem geometry were built [2].

The lifting surfaces installed under the hull, have a key feature of reducing drag during navigation due to the small *Wetted Surface Area* (WSA) of the boat [3], according to estimates, hydrofoils can decrease resistances by fifty percent in comparison to a similar

and comparable fast ship [4], leading to increased speeds, decreased power requirements, and a reduction in fuel consumption for motorboats. Although some applications of hydrofoil had already been used in racing sailing, the great diffusion of this technology began in 2013 thanks to America's Cup which for was regattated on foiling boats the first time in history. The great interest that has arisen, together with the technological development, has allowed the birth of new classes and new types of competitions; this is evident in the development of dinghies such as the *Moth* class [5] or in the case of daily cruiser motorboats. Furthermore, the use of software of numerical analysis (CFD, FEM, FSI) [6] and *Velocity Prediction Program* (VPP), which allows to simulate the behaviour of hydrofoils and the dynamics of the hydrofoil-hull system [7], have made it possible to speed up the design phases.

If the energy advantages caused using hydrofoil are evident, the design of this boat is challenging and together with the danger caused by the high speeds reached, means that these boats are used only in limited applications. Through the study of the state of the art, it was possible to investigate to evaluate what the main research areas are, identifying key aspects and design problems with the aim of directing research towards the use of this technology for a more sustainable boating which exploit the benefits of hydrofoils, reducing emissions without reaching the extreme performance of racing boats.

2 Introduction to Hydrofoil Sailing

Hydrofoils can mainly be divided into two categories in relation to the type of wing system (Fig. 1): The first, known as *piercing*, is characterized by a wing system designed with a *deadrise angle* $\delta > 0$ with respect to the horizontal, during navigation the tips of the wings come out from the water interacting with the free surface. The second category, called *fully submerged* hydrofoils, usually have $\delta = 0$ e and remain totally submerged during navigation [8].
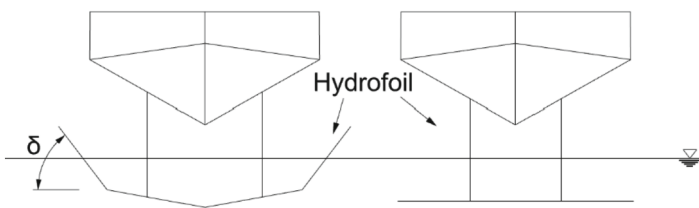
Fig. 1. Piercing hydrofoil vs fully submerged hydrofoil.

In an initial phase of motion these boats sail in a displacement mode (*hullborne sailing*), accelerating, the hydrodynamic forces of lift generated by the appendages enabled the hull to rise from the water's surface (*foilborne sailing*), eliminating shape and viscous drags and effectively reducing the impact of the waves [4] and making navigation more comfortable.

2.1 Types of Hydrofoil Boats

Hydrofoil technology can be used in various boat configurations, for example in the case of monohulls as for hydrofoil ferries [9], latest generation vessels or sailing classes such as the *AC75*. The most energy-consuming sailing phase for these types of boats is the take-off [10] as the wave resistance and viscous drags of the hull, partially submerged, add up to those generated by the hydrofoils. In some cases, the foils are also used to stabilize or partially lift the boat, reducing the WSA and improving fuel consumption. Also for multihulls, the use of submerged appendages, together with a different volume distribution compared to monohulls, allow, in sailing and motor boating, a reduction in drag is proven in several studies as in the case of and Suastika et Al. [11] on motor hydrofoil-assisted multihull.

2.2 Lift and Drag

The Lift of a hydrofoil is obtained as in the case of a classic wing [12]:

$$L = \frac{1}{2}C_L \cdot \rho \cdot v_\infty^2 \cdot A \tag{1}$$

Where, C_L is the Lift Coefficient, ρ is the density of the fluid $\left[\frac{kg}{m^3}\right]$, v_∞ is the relative speed of fluid-wing $\left[\frac{m}{s}\right]$ A is the wing surface in plan $\left[m^2\right]$.
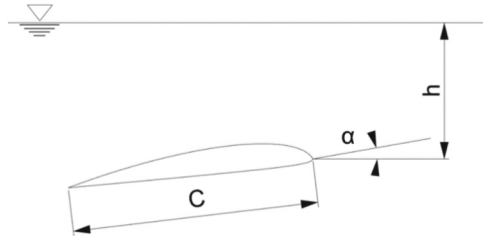
Fig. 2. Characteristic parameters of a submerged airfoil.

Furthermore, since we are in a multi-fluid environment and considering C as the chord, as verified by Parnold et Al. [13], C_L is almost constant if the submergence h is $h > 2C$. If the profile approaches the free surface and the wing is at $h = 0,911 \cdot C$, C_L, so the lift, increase by a few percentage points and if $h < C$ the C_L decreases drastically. Drag calculation turns out to be more complex as it is caused by various phenomena: in addition to the resistances generated by the profiles, it is necessary to consider induced resistances, sprays, viscosities, and interferences caused by the geometry of the wings and uprights [8].

3 Design Problems Identification

As previously stated, the purpose of this article is to identify the most active and most interesting areas to direct future research activities and for this reason, a deep bibliographic analysis was carried out. For our research, we utilized the Scopus database to

identify articles related to hydrofoils published in journals during the past decade follow-ing the 2013 edition of the 34th America's Cup, which marked the advent of hydrofoil technology in the maritime domain. From 2013 to 2023, the publication of papers in this area increased by approximately 300%. By investigating the keywords, we were able to pinpoint the major research areas of interest in the sector as illustrated in Fig. 3. In this paper, for reasons of maximum length, only the most soundness are cited. Once the major areas of importance were identified, it was then possible also to delve deeper into the topics, including articles predating 2013, to expand the knowledge.
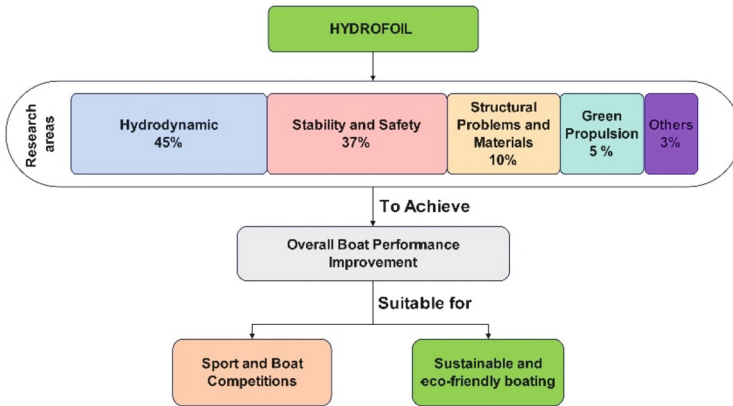

Fig. 3. Hydrofoil design, main design problems.

3.1 Hydrodynamic

From the results it can be stated that the most extensively addressed topic in the field of hydrofoils concerns the hydrodinamics of submerged wings. Although the characteristics of the profiles have been widely studied in aeronautics, the choice of the correct profile to use on a hydrofoil wing turns out to be a recurring topic since, in addition to the behaviour in terms of lift, drag and stall, it is also necessary to consider even to phenomena such as ventilation and cavitation. For these two reasons, the geometry of the airfoils used for hydrofoils and struts differs from aeronautical ones; if the speeds are higher than 40–45 knots ($Re \sim 10^7$), the use of profiles super-cavitating is necessary as they allow to delay the cavitation [14] and to avoid the sudden reduction in lift and increasing of drag. Moreover, for versatile foilborne navigation, Reynolds number calculated with the chord of hydrofoil can vary in a range between 10^4 and 10^7, resulting in a different hydrodynamic response of the wing which must necessarily have a system of mobile surfaces (flap) or a system to vary the overall incidence of the system.

If cavitation occurs when the pressure on the upper surface of the wing is so low that the water evaporates, the area affected by this problem is hit by the water and damaged due to the collapse of the steam bubbles, ventilation instead is linked to the interaction of the wings with the free surface and occurs in hydrofoil piercings or when

Fig. 4. Three different types of profiles: NACA 2412 (left), which is widely used to many aeronautical applications for low Re numbers; NACA 63–412 and Super-Cavitating (centre and right, respectively), two examples of profiles used to design hydrofoils.

fully-submerged wings get too close to the free surface. The low pressure causes the injection of air which, spreading along the entire span of the wing, drastically decreases lift, increasing drag and generating vibrations [15]. Ventilation is a characteristic of the piercing configuration of hydrofoils and is related to wing configurations with smaller δ (Fig. 1) and higher α (Fig. 2), additionally, profiles with sharp leading edges increase the likelihood of this phenomenon occurring [16]. The solutions proposed to stop this phenomenon are different, but one of the most common is the insertion of bulkheads or fences [17], which decrease the propagation of the air, increasing the WSA of the wing.

3.2   Stability and Safety

Another relevant topic concerns the analysis of boat stability and consequently both performance and safety. The behavior of a hydrofoil, especially if under sail, is particularly complex to evaluate because it is subject to a multiplicity of external forces, and this limits the use of these boats in restricted fields of application. To improve trim and safety, in numerous instances, a VPP is used to predict the dynamic response of the boat [18], which is subject, in addition to the hydroelastic behaviour of the wings, also to multifluid conditions. Considering that the lift is obtained from the relation (1) in which the surface A of the wing appears, a fundamental consideration can be made in terms of vertical stability: if the wing system is of the piercing configuration, also called *variable area foils*, the greater the speed, the greater the lift, the tips of the wings progressively come out from the water, self-balancing the system vertically and the foilborne flight will be stable. In fully submerged wing systems, with angle $\delta = 0$, increasing speed or because of external forces, such as wave motion, the wing can approach the surface of the water, varying its lift as expressed previously. Therefore, the fully submerged configuration is unstable and require a mechanical, or electronic control, which allows changing the lift of the wings making the boat stable, as in the case of the *wand* in the *Moth* class, to control the boat in free surface or waves and avoid capsizing [19]. Furthermore, the control of a large vessel, such as a ferry hydrofoil, turns out to be much simpler since the large inertia moments of the vessel make the system response to external forcing slower than in small vessels.

Hydrofoils can also be used to change the trim of the boat, partially lifting the hull with the aim of reducing the WSA and stability problems, as in the case studied by Shen et Al. in which a wing installed on the bow has allowed to improve performance and fuel consumption consequentially by always keeping part of the hull wet [20].

3.3   Structural Problems and Materials

A fundamental aspect also concerns the choice of materials, both for the wings and for the supporting structures. The latter two can be likened to beams which, interacting with

the fluid, are subject to stresses and moments that change over time, The most used materials for their construction are composite fibres, while steel is also used in some applications. In the design phase, in addition to structural dimensioning, hydroelastic issues are being referred to, such as the deformation of the wings under load and the vibrations induced by flutter. This phenomenon, known also as *singing*, could appears on the steel wings in the form of a high-tone sound, which, in addition to damaging the structure, is uncomfortable for the people on board [21], as well as causing continuous maintenance. To avoid structural problems, the analysis using *Fluid Structure Interaction* (FSI), such as the one carried out by Maung et Al. [22] on carbon fibre wings, can play a fundamental role also in evaluating hydroelastic response, according to loads and fatigue, allowing also the study of environmentally friendly materials, such as particular metal alloys or natural composite fibres which can be disposed of more easily at the end of their life.

3.4   Green Propulsion
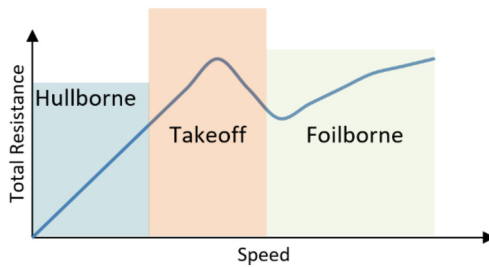
Fig. 5.   Total resistance curve for a hydrofoil boat.

In addition to the hydrodynamic and overall optimization of the vessel, the development of environmentally sustainable propulsion systems can give a push towards greater adoption of these vessels. In terms of optimizing fuel consumption, the use of electric propulsion coupled with hydrofoils is particularly suitable [23] as it allows the motors to be installed directly on the wing structures, allowing greater freedom in optimizing the fluid dynamics of the system. On the other hand, however, despite the low resistance generated, the weight and the battery capacity, do not allow for ranges of navigation comparable to traditional thermal-powered motorboats. For this purpose and considering the total resistance curve indicated in Fig. 5 [10], the development of hybrid engines that allow the delivery of maximum power in take-off, thanks to an electric motor, would allow the internal combustion engine to be used only in foilborne navigation when the total resistance decreases and the engine speed is constant, thus increasing the general efficiency of the propulsion unit and the sailing range.

4   Discussion

Based on the analysis of bibliographic articles, it is evident that in recent years, a large part of the scientific community has been directing its attention towards the development of hydrofoil technology as a means of enhancing the performance of boats.

The main themes addressed by the articles (82%) concern the hydrodynamic study and stability analysis of boats, as revealed by the analysis of keywords. Therefore, despite these topics having been extensively covered in literature, they remain highly relevant and represent areas of research that are still open to innovative solutions.

Furthermore, it can be stated that the pursuit of increased performance and improved stability in most studies is aimed at achieving better results in narrow usage contexts, such as the sports sector, and for fast ferries. The remaining part of the articles analysed deals with issues relating to the study of materials (10%) and, still to a lesser extent (5%), the use of green propulsion. However, it should be considered that if the intention is to leverage hydrofoil technology to create commercial green boats suitable for crews made up of non-professionals, the search for extremely high performance may not be necessary. To achieve a hydrofoil-based craft that is environmentally sustainable, it is essential to address, in addition to safety concerns, the topics that have received little attention in literature. For instance, the use of eco-friendly materials should be considered to facilitate the disposal of the vessel at the end of its life cycle. Simultaneously, expanding knowledge on the different types of propulsion could also lead to the development of environmentally friendly boats. As previously mentioned, the development of hybrid propulsion units could identify an optimal point between navigation range and ecological propulsion. Furthermore, a hybrid propulsion could equally reduce battery disposal problems compared to a full electric boat.

Lastly, to optimize the performance of hydrofoil boats even at lower speeds, a study could be undertaken on morphing profiles [24], this could be an idea to reduce the drag generated by the mobile surfaces and improve the wing performances, even in a wider range of Reynolds numbers. However, any problems related to use in a marine environment must be adequately evaluated.

5   Conclusions

Despite being invented years ago, hydrofoil technology has only begun to gain popularity in the boating industry in recent years and it can be a valid opportunity to reduce consumption and improve boat performance.

The work carried out has made it possible to identify research topics for the development of boats that do not require extreme performance comparable to racing boats, but which can equally take advantage of the benefits of using hydrofoils, making pleasure and commercial boating increasingly eco-compatible and respectful of the environment.

References

1. Johnston R.J.: Hydrofoils. Chapter V, Naval Engineers Journal, Feb (1985)
2. Matveev, K.I., Matveev, I.I.: Tandem hydrofoil system. Ocean Eng. **28**, 253–261 (2000)

3. Giovannetti, L.M., Banks, J., Turnock, S.R., Boyd, S.: Fluid Structures Interaction of High-Performance Catamaran C-Foils Under Load. 5th High Performance Yacht Design Conference, March 10–12. Auckland, New Zealand (2015)
4. Miranda, S.: Architettura Navale. Elementi di dinamica della nave. Liguori, Napoli (2014)
5. Findlay, M.W., Turnock. S.: Investigation of the effects of hydrofoil set-up on the performance of an international moth dinghy using a dynamic VPP. In: International Conference Innovation in High Performance Sailing Yachts, pp. 43–56. Lorient, France (2008)
6. Ruggiero, V., Morace, F.: Methodology to study the comfort implementation for a new generation of hydrofoils. IJIDeM **13**, 99–110 (2018)
7. Speranza, D., Di Bernardo, R., Martorelli, M., Gloria, A., Pensa, C., Papa, S.: Basic design and virtual prototyping of a hydrofoil hybrid daysailer. In: Gerbino, S., Lanzotti, A., Martorelli, M., Mirálbes Buil, R., Rizzi, C., Roucoules, L. (eds), Advances on Mechanics, Design Engineering and Manufacturing IV JCM2022, pp. 122–134. Springer (2023). https://doi.org/10.1007/978-3-031-15928-2_11
8. Odd, M.F.: Hydrodynamics of High-Speed Marine Vehicles. Cambridge University, Cambridge (2005)
9. Giallanza, A., Marannano, G., Morace, F., Ruggiero, V.: Numerical and experimental analysis of a high innovative hydrofoil. IJIDeM **14**, 43–57 (2020)
10. Vellinga, R.: Hydrofoils: Design, Build. Fly. Peacock Hill Publishing, Washington (2009)
11. Suastika, K., Nadapdap, G.E., Aliffrananda, M.H., Hermawan, Y.A., Utama, I.K.A., Aryawan, W.D.: Resistance analysis of a hydrofoil supported watercraft (Hysuwac): a case study. CFD Lett. **14**(1), 87–98 (2022)
12. Larsson, L., Eliasson, R.E.: Principles of Yacht Design, 5th edn. Adlard Coles, London (2022)
13. Parnold, L., Sacher, M., Wackers, J., Augier, B., Bot, P.: Free-Surface Effects on Two-Dimensional Hydrofoils by RANS-VOF simulations. The SNAME 24th Chesapeake Sailing Yacht Symposium. Annapolis, USA (2022)
14. Brizzolara, S., Federici, A.: Super-Cavitating Profiles for Ultra High-Speed Hydrofoils: a Hybrid CFD Design Approach. IX HSMV May 25–27 2011. Naples, Italy (2011)
15. Brizzolara, S., Young, Y.L.: Physical and theoretical modeling of surface-piercing hydrofoils for a high-speed unmanned surface vessel. In: 31st International Conference on Ocean, Offshore and Arctic Engineering, 1–6 July 2012. Rio de Janeiro, Brazil (2012)
16. Vermeulen, J.C., Barr, R.A, Martin, M.: Hydrodynamics of Hydrofoil Craft Subcavitating Hydrofoil Systems (1964)
17. Basic, M., Šarić, B., Basic, J., Blagojević, B.: CFD Analysis of Surface-Piercing Hydrofoil Ventilation Inception. XXII Theory and practice of Shipbuilding, Trogir, Croatia (2016)
18. Eggert, F.: Flight Dynamics and stability of a hydrofoilng international moth with a dynamic velocity prediction program (DVPP). Universität Berlin, D.M.S.T (2018)
19. Kebbell, S., Binns J.: Development of a full-scale moth hydrofoil control system test rig. In: The 9th Conference on Computational Methods in Marine Engineering, 1328 (2022)
20. Shen, H., Xiao, Q., Zhou, J., Su, Y., Bi, X.: Design of hydrofoil for the resistance improvement of planning boat based on CFD technology. Ocean Eng. **225**, 111413 (2022)
21. Matveev, K.I.: Maintenance of hydrofoil systems. High Performance Marine Vehicles, Hamburg (2001)
22. Maung, P., Prusty, B.G., White, J.M., David, M., Phillips, A.W., St John, N.A.: Structural performance of a shape-adaptive composite hydrofoil using automated fibre placement. Eng. Struct. **183**, 351–365 (2019)
23. Giovannetti, L.M., Farousi, A., Ebbesson, F., Thollot, A., Shiri, A., Eslamdoost, A.: Fluid-structure interaction of a foiling craft. J. Mar. Sci. Eng. **10**(3), 372 (2022)
24. Takahashi, H., Yokozeki, T., Hirano, Y.: Development of variable camber wing with morphing leading and trailing sections using corrugated structures. J. Intell. Mater. Syst. Struct. **27**(20), 2827–2836 (2016)