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Methodology for the Development of Hydrofoil Prototypes for High-Performance Windfoiling Using Additive Manufacturing

Abstract

This paper presents a methodology for prototyping hydrofoils for high-performance wind foiling using additive manufacturing. Previous research, based on reverse engineering and 3D model preparation for prototype production with aluminum molds, revealed notable economic shortcomings. A key challenge in producing and testing multiple prototypes lies in achieving the required mechanical properties while ensuring rapid mold and prototype fabrication. The production and preparation of aluminum molds often create a bottleneck in the process due to time and financial constraints, especially when several similar hydrofoil prototypes must be manufactured and tested in short intervals. This study demonstrates that additive manufacturing of molds provides high precision and sufficient mechanical performance required for vacuum carbon fiber lamination. Additionally, with post curing at appropriate temperatures, the molds maintain adequate strength for the production workflow. The prototypes were tested at a suitable testing site, and the results confirmed the effectiveness and practicality of the proposed methodology. This approach significantly shortens development time and lowers costs, which is essential for dynamic design and testing procedures in the field of wind foiling.

Keywords: methodology, additive manufacturing, prototype, hydrofoil, wind foiling

1. Introduction

This research is part of the project Framework for Developing Complex Geometry Hydrofoil Prototypes for High-Performance Wind-Foiling Applications, funded through the Uniri-Inova 4 program. The project builds upon previous work conducted within Uniri-Inova 2, where a methodology based on reverse engineering and the development of a digital twin was introduced to optimize the design and manufacturing processes of hydrofoils. While the earlier approach yielded excellent technical results, it lacked economic efficiency, particularly in scenarios requiring rapid iteration and production of multiple prototype variants.

The current project aims to establish a comprehensive methodology for selecting optimal fabrication strategies for complex-geometry prototypes tailored to elite sporting applications. This objective will be achieved by evaluating advanced additive manufacturing processes in combination with generative design principles and topological optimization of mold infill structures. The resulting molds will be used to produce carbon-fiber hydrofoil prototypes, which will subsequently undergo testing under real-world operating conditions.

An additional goal of the project is to strengthen collaboration between the academic community and industry stakeholders, enabling the proposed methodology—once validated—to be seamlessly transferred to broader engineering challenges beyond sports applications. Windfoiling and windsurfing are experiencing notable growth in popularity within the region, making them a relevant and practical testbed for this research. Accordingly, the methodology is applied in collaboration with top-level windsurfing athlete Mistral Matulja (Fig. 1), ensuring that the developed solutions are grounded in the performance requirements of high-level competitive practice.

2. Background

The implementation of advanced analytical methods, engineering techniques, and digital design tools to enhance competitiveness in high-performance sports has gained increasing scientific and practical relevance in recent years [1,2]. Although numerical simulation approaches—most notably those employed for detailed fluid-flow characterization—enable a high-resolution understanding of aerodynamic and hydrodynamic phenomena and facilitate geometry optimization for improved performance, the validity of such computational predictions must be rigorously confirmed through experimental verification [3]. This requirement necessitates the fabrication of physical prototypes and their subsequent evaluation under controlled or real-world operating conditions, a process that is frequently associated with substantial resource expenditure.



Figure 1. Test-pilot, top-level athlete in windsurfing - Mistral Matulja

Findings from prior research conducted within the Uniri-Inova project [4] revealed that the production of aluminum molds used for manufacturing prototype components with complex geometries constitutes a major economic and operational constraint. The temporal demands and financial burden of machining such molds significantly limit iterative design cycles and slow down methodological advancement. As an extension of this previous work, the present study aims to establish an integrated, resource-efficient framework for the fabrication of complex-geometry prototypes through the application of additive manufacturing technologies [5]. This approach is intended to reduce material consumption, shorten development cycles, and support rapid iteration within performance-driven design processes.

The successful realization of this framework requires a broad interdisciplinary foundation. Specifically, it entails:

- (i) conducting high-accuracy measurement procedures necessary for defining boundary conditions and validating numerical models [6,7];
- (ii) selecting and implementing appropriate numerical methodologies, ranging from steady-state CFD solvers to advanced turbulence-resolving approaches [8,9];
- (iii) understanding the operational principles, limitations, and parameter sensitivities of additive manufacturing processes relevant to mold and prototype fabrication [10]; and

(iv) possessing expertise in composite-manufacturing technologies, including vacuum infusion, vacuum bagging, or autoclave-based curing systems, as well as proficiency in real-environment prototype testing [11].

These activities collectively contribute to ensuring that the resulting components exhibit the required mechanical properties and that the hydrofoils perform reliably under predefined load cases and operational conditions. For quality-assurance purposes, material-characterization procedures must be performed both prior to the manufacturing stage [12] and immediately following production [13,14], before the components are integrated into a functional assembly.

Within the preceding Uniri-Inova project, the proposed methodology was primarily applied to the front wing of the hydrofoil assembly, whereas the present continuation extends and refines the methodological framework for application to the rear wing, as illustrated in Fig. 2.

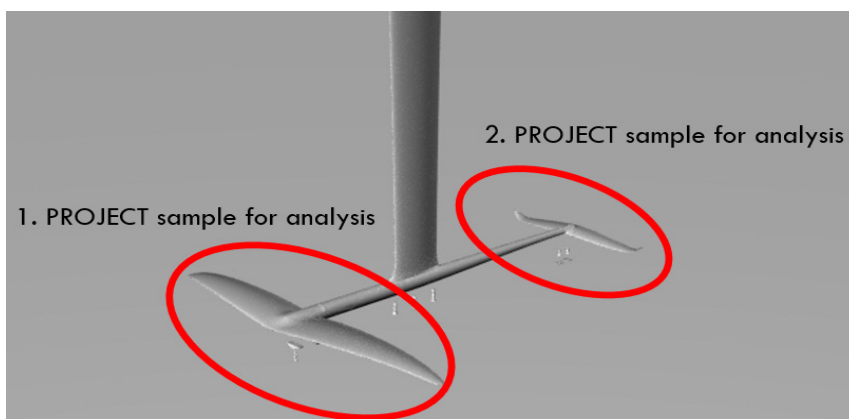


Figure 2. Analyzed hydrofoil system

3. Phases within the project

In the proposed project, the collaboration among several business entities—originally established during the first Uniri-Inova call—was successfully maintained and further strengthened. As anticipated, this collaborative framework provided a solid foundation for applying to additional research initiatives, including the submission of an extended research proposal to the Targeted Scientific Research call.

The methodology developed within this project, encompassing the creation of a digital twin, the establishment of a numerical framework for design optimization, and the integration of modern manufacturing technologies, is readily transferable to a wide range of engineering challenges. Such methodologies are already broadly applied in fields such as automotive and aerospace engineering, where their importance is internationally recognized due to their contribution to substantial technological

advancements and innovation. However, within the regional innovation ecosystem, these approaches remain underutilized, largely because collaboration between academic institutions and industry stakeholders is still sporadic and typically limited to isolated, individual efforts. For this reason, one of the project's central objectives was to actively promote collaboration between scientific and industrial partners, providing a model of best practice intended to inspire similar initiatives in the future.

The project successfully established a framework that enables researchers from various scientific domains to engage with industry and translate their innovations into practical applications. Notably, the involvement of multiple business entities encouraged several companies to allocate additional resources toward innovation-driven development, thereby further strengthening the link between academia and industry.

In line with the overarching objective—to develop a comprehensive methodology for manufacturing complex hydrofoil prototypes for elite sports using additive manufacturing, generative design, and topological optimization, validated through real-world testing and enhanced by strong science-industry collaboration—the project was structured into four distinct phases, as illustrated in Fig. 3.

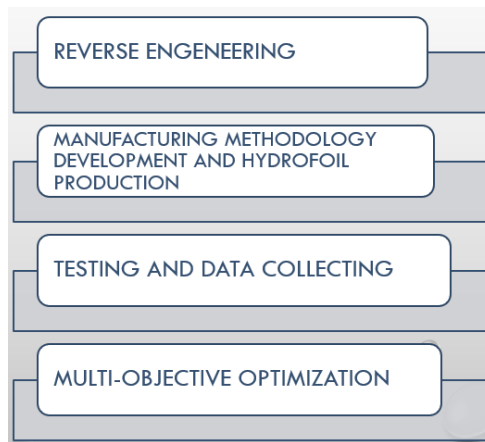


Figure 3. Phases within the project

3.1. Application of reverse engineering

The hydrofoil exhibiting the most favorable performance characteristics was identified through comparative evaluation and subsequently selected as the reference configuration for all further modifications and optimization procedures. Establishing such a benchmark model was essential for ensuring that subsequent design iterations could be quantitatively assessed relative to a validated and well-characterized baseline.

To enable high-fidelity geometric analysis and the development of an accurate digital twin, the selected foil was subjected to detailed three-dimensional acquisition.

The scanning process was carried out at the Center for Advanced Computing and Modeling of the University of Rijeka using a state-of-the-art 3D optical scanning system (Fig. 4). The employed scanner provides high-resolution surface data with minimal measurement noise, allowing precise reconstruction of the foil's geometry, including subtle curvature transitions and localized surface features that are highly relevant for hydrodynamic performance.

The resulting point cloud and surface models served as a foundation for subsequent computational workflows, including geometric refinement, numerical simulation, sensitivity analysis, and preparation for generative and topological optimization stages. This comprehensive digitalization step ensured that all downstream processes relied on an accurate and reproducible geometric representation, thereby increasing the robustness and scientific validity of the overall methodology.

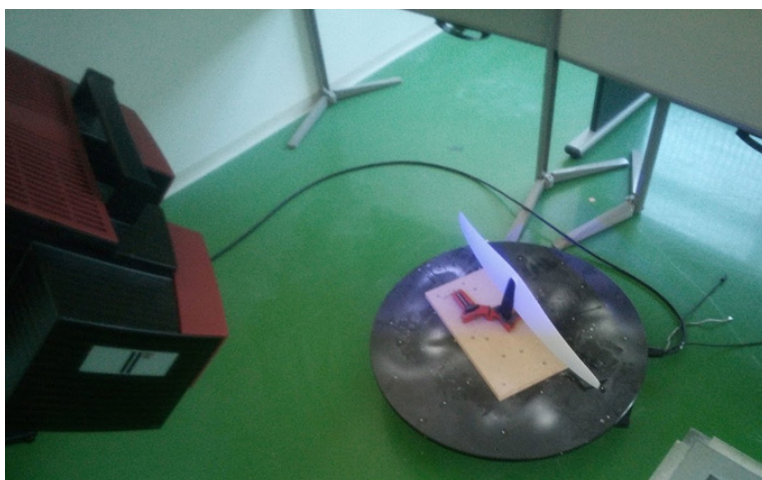


Figure 4. 3D scanning of selected foil

3.2. Creating a 3D model of prototype “zero”

The generated digital model was subsequently refined through targeted geometric modifications informed by both the measurement data obtained during scanning procedures and qualitative performance feedback provided by the test pilot. This dual-input approach ensured that the updated geometry not only preserved dimensional accuracy and structural consistency but also incorporated empirically grounded adjustments aimed at improving hydrodynamic behavior under real operating conditions.

The resulting configuration represents the new zero-prototype baseline, serving as the reference form for the next stage of physical production, iterative testing, and further design development (Fig. 5). Establishing such an updated prototype is essential for enabling controlled comparative assessments, validating numerical predictions,

and supporting subsequent optimization cycles within the broader methodological framework of the project.

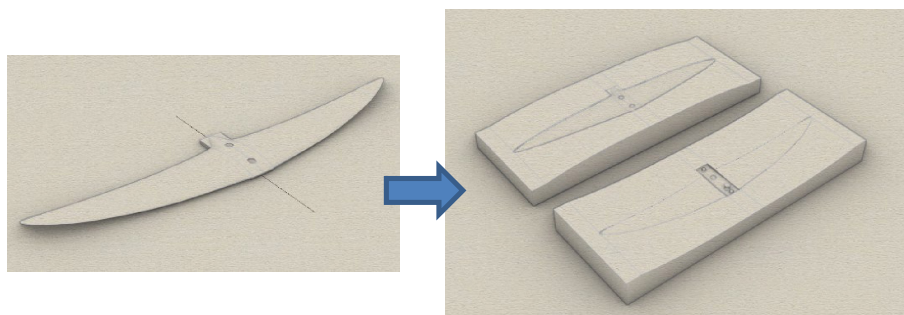


Figure 5. 3D model of the prototype and the mold

3.3. Manufacturing methodology development

Fabrication of single-use molds via additive manufacturing was carefully planned, ensuring full control over geometric fidelity and material performance. Following the 3D-printing phase, each mold underwent a targeted surface-finishing procedure designed to achieve the required smoothness and surface gloss essential for high-quality lamination. This post-processing step was crucial for eliminating micro-irregularities that could negatively affect fiber placement, resin flow, or surface integrity of the final composite component (Fig. 6).

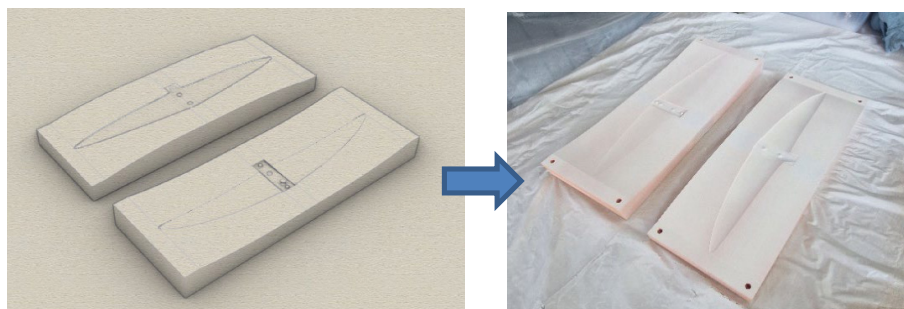


Figure 6. Mold preparation using additive manufacturing

3.4. Hydrofoil prototype production

The production of the high-modulus carbon-fiber hydrofoil began with CNC cutting of the carbon-fiber sheets according to the predefined lamination schedule, ensuring precise fiber orientation and structural consistency. The laminate was then

consolidated using a vacuum-bagging process conducted at a stable vacuum pressure of approximately -0.95 bar, which ensured adequate resin compaction and minimization of entrapped air. Following vacuum consolidation, the component underwent a controlled thermal-curing cycle to achieve the required mechanical performance and dimensional stability of the wing (Fig. 7).



Figure 7. Completed prototype

Particular emphasis was placed on advanced surface-treatment procedures aimed at eliminating micro-cavities and achieving a highly uniform aerodynamic surface finish. The post-processing workflow included multi-stage micro-sanding, progressive wet-sanding with fine-grit abrasives, mechanical polishing, and the application of high-precision surface-sealant coatings, all intended to minimize surface waviness and ensure high gloss. To verify the achieved surface quality, 3D optical profilometry, laser-scanning surface mapping, and interferometric surface analysis were employed, allowing detection of micro-scale irregularities critical for hydrodynamic performance.

Achieving this degree of surface integrity was essential for reducing friction-induced drag during experimental evaluations conducted using specialized high-precision measurement instrumentation (Fig. 8), which integrates motion-tracking sensors and an ultrasonic anemometer for real-time acquisition of kinematic and airflow data.

Prior to deployment, the measurement system underwent a rigorous calibration procedure. The motion-tracking sensors were calibrated using static and dynamic reference targets to ensure sub-millimeter positional accuracy across the full measurement volume. The ultrasonic anemometer was calibrated in a controlled flow environment using traceable reference velocities and a multi-point calibration curve, compensating for temperature, humidity, and angular alignment errors. This calibration protocol ensured synchronized, high-fidelity measurements of both wing kinematics and local airflow characteristics, thereby increasing the reliability and scientific validity of the experimental dataset.

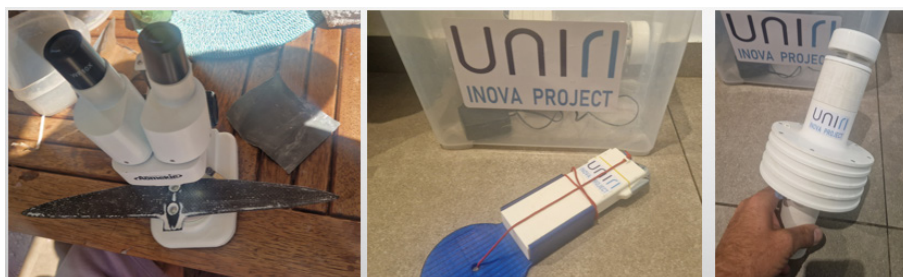


Figure 8. Testing preparation

3.5. Testing

The prototype was tested on a unique 10-km wind-foiling course in Gruissan, France, at the end of May, using specialized high-precision instrumentation tailored for real-world hydrodynamic performance assessment. The comprehensive dataset obtained during testing—comprising synchronized kinematic, aerodynamic, and environmental measurements—served as a critical input for the subsequent Computational Fluid Dynamics (CFD) analysis.

The CFD workflow involved the construction of high-fidelity numerical models aimed at reconstructing the flow field around the hydrofoil and quantifying its hydrodynamic performance envelope. Reynolds-Averaged Navier–Stokes (RANS) simulations were first employed as a baseline approach due to their computational efficiency and ability to capture mean-flow characteristics relevant for steady-state performance metrics such as lift, drag, and pressure distribution. To analyze transient flow phenomena, particularly those associated with tip-vortex formation, flow separation, and unsteady loading at higher angles of attack, Large-Eddy Simulation (LES) techniques were subsequently applied. The LES phase enabled resolution of larger turbulent structures while modeling only the smallest scales, thus providing deeper insight into vortex dynamics and energy dissipation mechanisms.

A hybrid meshing strategy was adopted, employing a refined boundary-layer mesh with $y^+ < 1$ to accurately resolve near-wall gradients, combined with a volumetric unstructured mesh further away from the surface to maintain geometric flexibility around complex curvature regions. Mesh-independence studies were performed across multiple mesh densities—ranging from coarse reference grids to highly resolved fine grids—to verify that key quantities of interest (lift coefficient, drag coefficient, and pressure integrals) converged within an acceptable tolerance margin ($< 2\%$).

Convergence analysis relied on monitoring the normalized residuals of the governing equations, ensuring reduction by at least three orders of magnitude, alongside stabilization of integral force coefficients and characteristic flow features. Temporal

convergence in LES runs was validated through Courant-number control and sufficient sampling interval lengths to guarantee statistically stationary flow averages.

The combined results of RANS and LES simulations informed a set of targeted geometric refinements, particularly in regions of flow acceleration and trailing-edge pressure recovery. These refinements will guide the fabrication of a second-generation prototype expected to exhibit improved hydrodynamic efficiency and stability. The final prototype will undergo additional validation testing and is planned to be showcased at the next year's World Championships (Fig. 9), providing an opportunity for performance benchmarking against elite-level equipment.

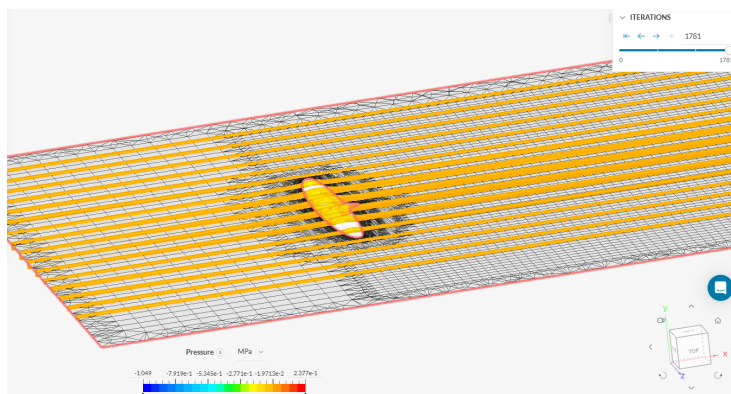


Figure 9. CFD analysis.

4. Conclusions

A substantial bidirectional knowledge transfer was achieved throughout the project. Insights obtained from real-world testing and measurement activities—conducted in close collaboration with a professional pilot—provided the academic community with empirically grounded and highly relevant performance data. In parallel, industry partners contributed essential domain expertise, enabling the research team to develop a deeper understanding of production-feasible engineering solutions, associated technological constraints, and implementation challenges. This synergy between empirical research and industrial practice significantly enhanced the technological readiness and applied-research capabilities of the academic investigators.

The involvement of faculty researchers in the development of high-performance engineering applications not only contributed to advancing scientific understanding but also strengthened their competitiveness in future industry-oriented research initiatives. Moreover, the methodologies established within this project demonstrate broad applicability beyond sports-specific hydrodynamic systems, offering a transferable framework for solving complex engineering problems across diverse product development domains. As a result, the project has contributed to increasing both the

visibility and strategic impact of the University within the wider innovation ecosystem.

Additionally, the project has laid a strong foundation for securing further long-term research initiatives, which are expected to enhance institutional prominence and stimulate greater student engagement in applied research activities. The deliberate inclusion of several early-career researchers provided them with exposure to the full lifecycle of an industry-collaborative project—from concept development to experimental validation—thereby fostering critical professional networks and promoting their future independence in securing competitive research funding. Collectively, these outcomes underscore the project's broader scientific, educational, and developmental significance.

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