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Development of Small-Scale Unmanned Hydrofoil Boats

Noah T. Thompson, Phillip R. Whitworth and Konstantin I. Matveev¹

School of Mechanical and Materials Engineering, Washington State University, Pullman, WA, 99164, USA

Abstract: Unmanned boats have gained a lot of interest in the maritime community during the last decade. Most hydrodynamic platforms employed for unmanned boats are based on traditional relatively simple hulls. In the present study, small-scale hydrofoil-assisted unmanned boats (0.6-0.7 meter in length and 3.5-5.5 kg in mass) have been developed and tested. Design calculations using a hydrodynamic transverse-strip engineering method with semi-empirical correlations were applied to determine suitable dimensions for hydrofoil systems. The boat hulls and hydrofoils were fabricated by laying up carbon-fiber cloth sheets on foam cores or 3D printed profiles. The boats were instrumented with outboard propulsors and electronic equipment for operations in both remote control and autopilot modes. In addition, an in-situ thrust-measuring module was designed and installed at the hull sterns to gather thrust data at GPS-measured speeds in the range between 0 to 11 m/s. The developed boats proved to be robust platforms capable of going over 600 m distances at high speeds while autonomously following preset paths. The presented methods and results can assist engineers developing unmanned surface vehicles that utilize advanced hydrodynamic concepts.

Key words: unmanned surface vehicles, hydrofoils, autopilot, remote control, load cell.

¹ Corresponding author. E-mail: matveev@wsu.edu

Introduction

The unmanned marine vehicle technology has been rapidly growing in recent years. For example, autonomous ferries have started operating in Norwegian fjords (Torben 2018). Unmanned underwater vehicles have been broadly applied by the offshore industry and navies and for scientific purposes (Capocci et al. 2012; Antonelli 2010). Transoceanic cargo vessels without crew are envisioned to appear in the near future (Batalden et al. 2017). However, in the area of unmanned surface vehicles (USV), most efforts have been put in the development, adaptation or integration of sensors, electronics, and algorithms (Campbell et al. 2012; Liu et al. 2016), while the hull configurations of autonomous marine platforms remain relatively simple from the hydrodynamic standpoint. Some examples of recent studies include three-degree-of-freedom propulsion modeling and experiments on USV (Mu et al. 2018), distributed containment maneuvering controllers for underactuated USV's (Gu et al. 2019), and development of a novel obstacle tracking method for USV (Muhovic et al. 2019). Small, about 1-meter-long USVs comparable in size to the boats described in this paper have been also constructed by researchers, including airboats (Valada et al. 2012), catamarans (Sohn et al. 2015), and fast planing hulls (Grenestedt et al. 2015). However, these and most other developed so far USV's involve either traditional monohulls or slow but spacious multi-hulls.

There are a variety of missions where USV with special hulls or performance-augmenting hydrodynamic means can be of great benefit. For example, amphibious platforms can operate on both water and ground (Chaney et al. 2012), while the so-called small-waterplane-area hulls (Brizzolara et al. 2011) have exceptional seaworthiness that can be especially valuable for small USV operating in open seas. In this study, we are addressing another class of advanced hydrodynamic configurations that use hydrofoils for partially or completely supporting the vehicle weight (Fig. 1). Hydrofoil-assisted boats are usually more

efficient than traditional hulls at higher speeds. Hydrofoils can also damp wave-induced motions and loads, thus improving boat seaworthiness in waves. Hydrofoil boats were rather popular in the second half of the last century (McLeavy 1976; Saito et al. 1991), when they were employed as ferries for passenger transportation in coastal regions, between islands, and along rivers. However, their performance was usually optimized for specific operational conditions and their foil systems required special maintenance.

With greater availability of materials, such as composites, and with advances in control systems, the relative cost of building more efficient and possibly adaptive hydrofoils is not as significant as in the past. The potential performance improvement makes this technology rather attractive. For example, light composite hydrofoils are already applied for use on high-speed sailing yachts, where weight is a concern (Giovannetti et al. 2018). The objectives of the effort described in this paper were to develop demonstrators of small-scale unmanned hydrofoil-assisted boats that can reach high speeds and to initiate applications of autonomous methods for these craft. Given the exploratory nature of this work and constraints in time and resources, the main focus was made on developing robust demonstrators rather than optimizing vehicle for specific regimes, which leaves significant room for future improvement and evolution.

Materials and Methods

Selection of Hulls and Hydrofoils

As the starting point in designing the boats in this project, the hull dimensions were specified as about 61 cm in length and 16 cm in beam. Additional extensions in the length and beam were allowed for the

entire platform to accommodate an outdrive propulsor behind the stern, wider hydrofoil systems on the monohull, and outriggers on the trimaran. For the hull shapes, simple constant-deadrise and mainly prismatic forms tested in the past (Fridsma 1969) were chosen for simplicity of construction and connections with hydrofoil systems (Fig. 3).

In order to appropriately select the hydrofoil dimensions, the hydrodynamic calculations for boats in foilborne regimes were carried out using the engineering method commonly used for initial design of Russian-style surface-piercing hydrofoil systems (Kolyzaev et al. 1980; Voitkunsky 1985; Matveev and Duncan 2005). In this method, the hydrofoil is divided into several segments in the spanwise (transverse) direction, as illustrated in Fig. 2a. For each segment, lift and drag coefficients are evaluated based on semi-empirical correlations that account for the profile geometry, local deadrise, segment submergence, and location inside the foil system. For example, the lift coefficient is calculated as follows,

$$C_L = \frac{k_1 \left(\frac{\partial C}{\partial \alpha} \right)_0 (\alpha + \Delta \alpha)}{1 + \frac{k_2}{\pi \lambda} \left(\frac{\partial C}{\partial \alpha} \right)_0}, \quad (1)$$

where α is the effective incident flow angle accounting for the foil orientation and relative vertical velocity, $\Delta \alpha$ is the angle correction due to profile asymmetry and free surface, k_1 is the lift slope correction accounting for free surface and segment position along the span, $\left(\frac{\partial C}{\partial \alpha} \right)_0$ is the lift slope of the two-dimensional foil that includes an approximate viscous correction, k_2 is the correction for downwash due to presence of struts and free surface, and λ is the hydrofoil aspect ratio. After determining hydrodynamic coefficients of hydrofoil segments, the entire forces on hydrofoils are evaluated. A

general goal of the present boat design was to achieve speeds corresponding to the displacement-based Froude number Fr of about 6. This Froude number is defined as follows,

$$Fr = \frac{U}{\sqrt{g^3 V}}, \quad (2)$$

where U is the boat speed, g is the gravity constant, and V is the volumetric displacement. Only small-scale boats were considered in this study, and no scaling to or design of large-scale boats was attempted.

With information about hydrofoil forces, the boat dynamics is then simulated using a 3-DOF model for heave-pitch-roll motions at a given operational speed. These simulations were conducted in Matlab for a range of expected speeds. In addition, roll and pitch stability are checked. An example of estimated hydrofoil positions on a boat steadily moving at a constant speed is shown in Fig. 2b-d. While these calculations are certainly very approximate, they can quickly give an idea about suitable foil positions and sizes to produce adequate lift and ensure stability. As concerns drag forces, accurate prediction of resistance was not aimed at. The calculated hydrofoil-only drag would underestimate the total drag due to neglect of spray and strut drag, detrimental but unknown scale effect, and expected imperfections in the foil system construction. In order to address this uncertainty of drag calculation and variable boat weight (that may need to carry different payloads), readily available high-power propulsion units were employed in this project.

The hull lines and foil profile with main dimensions are schematically shown in Fig. 3. Some dimensions of the foil systems and outriggers on two designed boats are also depicted in Figs. 4-5. The convex-flat foil profiles were made of chord 3.6 cm and thickness 0.45 cm. The installed hydrofoil angles and vertical positions were adjusted during tests for specific payload and weight distributions. The typical installed

angles were around 5° for the fore foils and zero or even negative values for the rear foil on the monohull, whereas gaps between the foils and keel lines were between 1.5 cm to 5 cm. The wide hydrofoil systems on the monohull and outriggers on the trimaran were employed primarily to ensure lateral stability of the boats and relatively sharp turns at high speeds.

System Construction and Assembly

Two types of foil-assisted boat configurations were designed in this project: a monohull (Fig. 4) and a trimaran (Fig. 5). Both boats were constructed to be as modular as possible. The monohull has fore and rear foil systems of surface-piercing kind, each with adjustable trim and depth below keel. The trimaran has a simple flat hydrofoil at the bow with adjustable trim and depth, whereas positions of the outriggers can be varied with respect to the main hull. The masses of setups tested during the project were between 3.5 to 5.5 kg, depending on payloads and equipment. The thrust and steering were accomplished using compact but powerful outdrive propulsors, such as Pro Boat and Hyperformance (Offshoreelectronics 2019), steered with help of servo motors. The main criteria for selecting propulsors were that they could deliver high thrust (above 30 N), be of outdrive type for convenience of changing their positions and installing a load cell between propulsor and hull. These propulsors used brushless motors with optional water cooling and flex shafts to deliver power to propellers. Images of the propulsor are given in Fig. 6. A propeller was usually positioned about 15-20 cm behind the transom and 5-8 cm below the keel.

The hulls and foils are made of foam cores covered with carbon-fiber layers for increased durability in testing and ease of manufacturing complex shapes quickly. A combination of fused deposition modelling (FDM), CNC machining, laser cutting, and wet-layup composite processes was used in the manufacture

of foils and other small structural components. To create hull shapes, components of foam cores were cut using a two axis CNC hot-wire cutter (Fig. 7a). These cores were then combined and sanded to create complete hull forms. Hulls were wrapped in carbon fiber and allowed to cure at room temperature (Fig. 7b). Foil and motor mounts were machined from carbon-fiber plates to a higher precision, then bonded at appropriate locations to the hull base. Cavities were carved from the hull foam core for payloads and some of electronic equipment.

Hydrofoil sections with flat bottom surface and convex upper side were made of carbon-fiber reinforced FDM printed parts. A printed section was lined on the bottom side by a single layer of carbon fiber cloth, then cured under vacuum pressure. Foam core vacuum layup processes were also explored, but ultimately yielded unsatisfactory adherence to intended foil geometry. Even our best hydrofoil sections had surface imperfection up to few percent of the foil chord, especially near struts. The struts holding hydrofoils were cut from carbon-fiber sheet with a CNC router, then bonded with the foil sections using a fillet of short-strand, discontinuous carbon fiber. Interchangeable mounts for the multihull's outriggers were made with FDM. The cross member connecting the three hulls was made of aluminum bar.

The diagram of the overall electronics system assembly is shown in Fig. 8. The autonomous control system was built around a Pixhawk PX4 platform (Fig. 9a). 915 MHz SiK radios and Here 2 UbloxM8P GPS module were selected for their compatibility with this platform. The PX4 communicates with a 2.4 GHz Futaba S2008SB receiver via SBus. It is through this receiver, a traditional RC interface, that autopilot is initiated. The GPS module communicates with the PX4 using CAN bus. For the autonomous mode, the autopilot configuration and mission planning are accomplished through the Mission Planner software included in the Ardupilot suite. However, in most initial tests when modified boat/foil versions were

164 experimented with, only manual remote-control mode through Futaba transmitters and receivers was
165 used without the autopilot hardware.

167 A video transmission was also employed in some tests with the purpose to monitor boat functions of
168 particular interest from afar. The power for the video module came directly from the main battery loop
169 to run a 5.8 GHz transmitter with an internal voltage regulator. The AV receiver was connected to a
170 portable 5" screen, powered by its own battery.

172 In the later stage of the project, the thrust-measuring system was implemented on the boats. That
173 required modifying the propulsor mounts, so the outboards were connected to the hulls via a button-
174 type 110-N-capacity load cell (Fig. 9b). These changes also required raising a thruster to avoid excessive
175 drag and spray produced by the propulsion unit mounted further downstream from the stern. The hull
176 bottom at the transom was extended with thin plates by about 5 cm to reduce drag induced by the
177 additional mounting plates. Because of higher thruster elevation, the hull stern had to be kept closer to
178 water to avoid propeller ventilation, especially on the monohull setup with the rear foil. As expected,
179 these modifications resulted in some degradation of the boat hydrodynamic performance, but provided
180 a capability to measure thrust in-situ.

182 Geographical location, groundspeed, GPS time, and thrust were then collected with a separate
183 electronic assembly (Fig. 10). This data acquisition system was independent of the control system, and
184 did not transmit to shore. All data were logged to an SD card. Another GPS was employed for easy
185 correlation of time, speed, and force. An HX711 analog to digital voltage amplifier board was used as an
186 interface between a millivolt output force load cell and an Arduino Mega 2560. The load cell had a

regulated excitation voltage to it directly from the Arduino. The load cell was calibrated onshore prior and after each test.

Results

The developed in this project boats were operated in various speed and loading regimes. They successfully run at speeds up to 12 m/s over distances of about 600 m in both manual radio control and autonomous (via waypoints) modes. In configurations with the load cell installed, the boats were tested in more restricted water reservoir of about 50 m long. The highest speeds of the boats in this pond were somewhat lower due to limited size of the testing range. Illustrations of the boats in the foilborne regimes were shown in Fig. 1 in the beginning of the paper.

The sample results for the thrust and achieved speeds in the configurations with the load cell installed are given in Fig. 11a. The overall boat masses were around 5.5 kg in these tests, and the center of gravity was at about 37% of the boat length from the hull transom forward. The measured thrust was corrected to approximately account for deviations of the thrust line from the horizontal axis passing through the boat centerplane. These deviations were due to non-zero installed propulsor angles with respect to the hull keel line and due to the yaw angle applied to the propulsor to counteract cross wind loads during testing.

The thrust-speed data look approximately similar for both the monohull and trimaran setups. The monohull needs lower thrust at lower speeds due to its smaller hull surface area, but it requires higher thrust at higher speeds due to necessity of keeping the boat stern close to the water surface in the configuration with the load cell, by way of making the installed angle of the rear foil slightly negative.

211

212 There are gaps in data point sets at the intermediate speeds between 1-3 m/s for the monohull and 3-5
213 m/s for the trimaran (Fig. 11a). These speeds belong to the transitional regime from the displacement
214 mode, when hydrostatic support is more important, to the dynamically supported regime, when lift
215 from hydrofoils and planing surfaces becomes dominant. At the transitional speeds, the vehicle drag
216 may decrease with increasing speed. If a throttle is kept the same, the boat accelerates up to higher
217 speeds, at which drag increments become positively correlated with speed variations. Hence, hydrofoil
218 boats usually quickly pass through the intermediate speed regimes.

219

220 Illustrations of the trajectories of the monohull boat operating in the autonomous path-following mode
221 in the small water reservoir are shown in Fig. 11b,c. At low speeds, the boat can follow the prescribed
222 path rather closely (Fig. 11b). At a higher speed, the boat cannot make the sharp turn (Fig. 11c), and
223 hence, overshoots the desired trajectory. However, the boat eventually comes back to the prescribed
224 path. In the large water reservoir and with long distances between waypoints, the boat (in the original
225 setup without the load cell) was able to follow the assigned paths even at high speeds approaching 10
226 m/s, but data were not recorded in those tests.

227

228 During the development process in this project, several technical issues were discovered and addressed.
229 Due to operations of the small hydrofoil boats in different speed regimes, the hull motions, spray, and
230 waves make it easy for water to reach the top surface of the boat, so a special attention needs to be
231 paid to making the payload-carrying compartments in the hull watertight and minimizing open spaces to
232 reduce the amount of taken water. While the brushless motors, batteries, and marinized electronic
233 speed controllers were not affected by water, the conventional receivers and servomotors required
234 careful water proofing. Rare mechanical failures included flex shaft damage, which might be caused by

propellers operating in the presence of seaweed in water, and hydrofoil displacements caused by collisions with other objects.

Discussion

In this project, two high-speed small-scale hydrofoil-assisted platforms were developed, including a monohull boat with fore and rear foils and a trimaran with a fore foil only. The hydrofoil dimensions were initially selected with the simplified engineering calculation method, whereas foil positions and orientations were adjusted during tests. With use of carbon-fiber layers, the constructed hulls and hydrofoils proved to be resilient in the extensive testing program. Different electronics control arrangements have been implemented, including a simple manual remote control, as well as autopiloting along a prescribed path. The setup for measuring thrust force and collecting data was also designed and assembled, and speed-thrust correlations were recorded. The main objective of the present work to develop and demonstrate robust fast unmanned hydrofoil boats has been achieved.

Hydrofoil craft operate at high speeds more economically and have better seakeeping characteristics than traditional fast boats (McLeavy 1976), but hydrodynamic analysis, fabrication, and operation of hydrofoils are more complex in comparison with conventional hulls. At the same time, there is a lack of literature on hydrofoil USV, since most platforms employ relatively simple mono- and multi-hulls (Valada et al. 2012, Sohn et al. 2015, Grenestedt et al. 2015). The main contributions of the current study include demonstration of feasibility of hydrofoil applications for small USV and description of design methods, manufacturing, instrumenting, and running hydrofoil boats in both remote control and autopilot modes. The presented here information should be helpful for researchers without experience in hydrofoils but interested in developing their own hydrofoil USV for high-speed applications. In

particular, simplified strip-type calculations based on methods similar to wing aerodynamics but accounting for free surface effects can be used to determine hydrofoil dimensions sufficient to support the boat weight (Matveev and Duncan 2005). The subsequent in-situ testing with variable foil positions can then be used to optimize the boat performance for specific operational conditions.

The possible future directions can involve optimization of the hull hydrodynamics and propulsion system elements. Implementing automatic control for foil positions will help achieve high performance in a broad range of speeds, payloads, and environments (Saito et al. 1991), and can include foil retraction to make the hull efficient at low speeds and to provide capabilities for shallow-water/landing operations. Usage of light composite materials with anisotropic properties can also improve hydrofoil boat performance (Giovannetti et al. 2018), but more pronounced fluid-structure interactions and complex failure mechanisms will need to be analyzed. Advanced autonomy modes, such as target tracking, collision avoidance, and swarm operations, can be realized with additional instrumentation and more sophisticated control approaches (Campbell et. 2012). However, one has to bear in mind that hydrofoil boat dynamics in high-speed foilborne regimes is rather different from that of displacement hulls (Matveev 2020), so dynamics models commonly used for conventional boats will need to be modified.

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Figure captions

Fig. 1 Hydrofoil-assisted monohull and trimaran developed in this study.

Fig. 2 (a) Front view of hydrofoil system with dashed vertical lines showing division of hydrofoils into segments for calculating hydrodynamic characteristics. (b-d) Schematic views of hull and hydrofoil positions produced by calculations for one monohull arrangement at forward speed 4.5 m/s. Foil span lines and segment centers are shown in red. Hull bottom in front views and keel in side view is shown in black. Center of gravity is depicted by circle in (b). Water surface (deformed behind fore foil) is shown by dashed blue line. Fore-foil installed attack angle is higher than rear-foil angle.

Fig. 3 (a) Side and (b) front view of constant-deadrise hull. (c) Hydrofoil profile.

Fig. 4 Main dimensions of hull and foil systems on monohull boat. The aft foil has shorter inclined sections, but otherwise is similar to the fore foil.

Fig. 5 Main dimensions of hull and foil systems on trimaran boat.

Fig. 6 Side and top views of outdrive propulsor.

Fig. 7 (a) Hull shape being cut from foam by hot wire, (b) vacuum bagging of carbon-fiber lay up during adhesive cure.

Fig. 8 Diagram of electronic components.

Fig. 9 (a) Watertight box with flight controller. (b) Setup for thrust-measuring load cell and outdrive propulsor.

Fig. 10 Electronics assembly for load cell GPS data: (a) block diagram, (b) hardware implementation.

Fig. 11 (a) Recorded thrust and speed data: circles, monohull; squares, trimaran. (b-c) Boat trajectories (purple lines) in autonomous modes with speeds of (b) about 1 m/s and (c) about 4 m/s. Yellow line connects prescribed waypoints. The autopilot boat symbol is not-to-scale (much larger than the actual vehicle size).

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