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Foiling Autonomous Surface Vessel: Project C-Flyer

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ABSTRACT

Project C-Flyer is a concept design of a hydrofoiling autonomous surface vessel specifically created to be a first responder in search and rescue scenarios.

Over 40% of Royal National Lifeboat Institution (RNLI) callouts do not require manned assistance but still put the voluntary lifeboat crews in harm's way. C-Flyer provides the means to identify these cases significantly earlier. With autonomous launching, C-Flyer can reach over 85% of callouts before a manned lifeboat would ordinarily be launched. This allows for an opportunity to assess whether the lifeboat is required or to provide other emergency services with critical information that may help save a life.

The four-metre vessel is capable of detecting persons in the water at a distance of up to 4.9nm, and, when attending an incident, the speakers and microphone allow for two-way communication between individuals and a land-based operator. The onboard, hydrogen-powered systems allow for environmentally friendly operation whilst still enabling the vessel to reach speeds of over 35 knots. Finite Element Analysis was used to analyse the hull structure and to ensure that C-Flyer could operate in the wide range of sea-states found in the English Channel.

C-Flyer takes full advantage of hydrofoils and autonomous technology and was designed with modularity in mind so that, with only minimal changes, it would be possible to perform other roles such as security or scientific research.

INTRODUCTION

Autonomous Surface Vehicles

Autonomous Surface Vehicles (ASVs) are marine crafts capable of performing unmanned operations whose existence dates back to the Second World War [1], [2]. In the 1990s, the large proliferation of academic and military research associated with technological advancements enabled for more capable systems to be built [3]. Since then, ASVs have seen a sharp rise in number and overall capabilities.

The ASV market was estimated to be worth $534m in 2018 and projected to reach more than $1bn in 2023 [4] (Figure 1). Such projections show the extent to which these vessels have become commercially viable and formed the basis for successful business models.

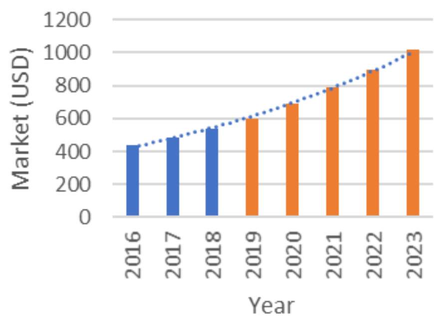

Figure 1: ASV market predictions [4]

ASVs vary in size, configuration and application. Traditionally, these systems have been adopted for defence purposes; however, the scientific and commercial sectors have recently begun to make more use of ASVs for their specific purposes. Depending of the role of the vessel, ASVs can range in length from one metre to 90 metres, with the possibility of 200-metre ASVs being available in the near future [5].

The success of ASVs can be largely attributed to one primary advantage; namely that removing the human operators allows for new modes of operation.

Hydrofoils

The concept of using hydrofoils to reduce hull drag has been in existence for at least 100 years. Reports suggest that in 1906, the Italian inventor Enrico Forlanini designed and built the first successful hydrofoiling vessel, employing ladder foils to do so [6]. Similar to an airplane wing, hydrofoils generate lift by inducing a pressure difference between the two faces of the foils [7]. As a result, the hull can be lifted out of the water thus reducing drag at higher speeds and limiting wave-induced motions due to the much smaller immersed volume. However, contrary to airplane wings, the development of hydrofoils was slow over the years due to the differences in economic forces between the aviation and shipping industries.

Figure 2: Enrico Forlanini's hydrofoil on Lake Maggiore [8]

Hydrofoiling vessels were traditionally expensive to build, maintain, and operate, and carried relatively few people over short distances. Reports from the 1980s on the Southampton to Cowes hydrofoiling route suggest that there was sufficient demand for larger vessels. However, a larger vessel capacity generally requires larger foils which prevent the vessels from docking in low tide ports [9]. Hydrofoiling vessels have also, at times, struggled with safety issues. Neil Baird at the University of Wollongong, Australia showed that 30% of total fatal incidents involving fast passenger ferries have been caused by hydrofoiling vessels, despite these only accounting for 13% of the fast passenger ferry fleet between 1966-2015 [10]. However, recent technological progress in composite materials such as carbon fibre has enabled a new generation of designs to be created.

Maritime Search & Rescue in the UK

The Royal National Lifeboat Institution (RNLI) keeps detailed operational statistics that give substantial insight into the conditions in which search & rescue services operate as well as the variety of callout outcomes [11]. These statistics reveal that, in 2018, over 40% of callouts resulted in no manned assistance being provided. In addition, 83.4% of callouts were in a force four windspeed or less, and, of callouts where the casualty was located, 97.4% of these were within 15 nautical miles of the coast.

DESIGN BRIEF

The design brief of this project was to design a hydrofoiling ASV to act as a first responder for search and rescue scenarios in UK waters. In order to be an effective design, the following primary design requirements were specified:

1. A minimum speed of 30 knots
2. A minimum range of 24 nautical miles
3. Able to operate in 80% of sea states found in the English Chanel
4. Launch and recovery systems compatible with existing RNLI systems
5. Sustainable design and operation
6. A self-righting hullform

In addition, the design was to comply with relevant rules and regulations where appropriate, and it was decided that the design should retain an element of modularity to enable the base hullform and propulsion system to be used for alternative purposes.

METHODOLOGY

Hull Design

The hull design was a critical part of the design. Up to take-off this will be the primary source of drag. Consequently, the hull had to be carefully considered from the start of the design process.

Hull dimensions were primarily driven by payload requirements and analysis of a range of basis vessels. From a regression of fast craft data is was found that the payload was in the range of 10%-15% of the vessel's displaced weight. Initial payload calculations of 70kg meant that the displaced weight would be in the range of 700kg. Regression analysis then enabled major hull parameters to be chosen, as shown in Table 1.

Table 1: Initial hull parameters

Speed	12.0	kts
Payload mass	70.0	kg
Vessel mass	700	kg
Length	4.00	m
Beam	1.60	m
Draught	0.35	m
Deck height	0.78	m

Following the definition of hull parameters, some important performance characteristics were identified. The hull should have a sufficiently smooth ride to provide the foils with a stable angle of attack and prevent stalling or sudden take-off. Additionally, good roll stability is desirable. Finally, to facilitate take-off, the hull should generate hydrodynamic lift. To choose the most adequate hull characteristics, an analysis of existing hulls was performed. A monohull was deemed preferential due to the lower structural weight and reduced resistance - both key for foiling ability.

The expected take-off speed equated to a Froude number of 0.97, implying a planing hullform would be appropriate. Planing hulls are typically straight-bottomed with either a completely flat or V-shaped bottom to generate hydrodynamic lift. These bottom shapes usually finish in hard chines running along the side of the vessel, which help with roll stability [12].

The basis vessel design [13] was replicated and scaled using the Maxsurf suite of ship design software. The hull lines were initially produced based on the monohedron lines procedure whilst also implementing some of the cissoid lines approach. The monohedron lines approach ensures constant lift and little transom suction. The cissoid lines approach, on the other hand, ensures that there is a soft riding entrance and advantageous wave reflection properties. In addition, this is also one of the few processes that is formula-based, meaning good results can be replicated more easily. The refined hull design is shown in Figure 3 and the particulars in Table 2.

Table 2: Refined hull parameters

Draft Amidships	0.354	m
WL Length	4.083	m
Beam max extents on WL	1.347	m
Chine	1.1	m
Wetted Area	5.492	m^2
Displacement	0.7529	tonnes
Waterpl. Area	4.123	m^2
Prismatic coeff. (Cp)	0.696	
Block coeff. (Cb)	0.346	
Max Sect. area coeff. (Cm)	0.58	
Waterpl. area coeff. (Cwp)	0.75	
LCB from aft	1.584	m
LCF from aft	1.613	m
Trim angle (+ve by stern)	-2.080	m

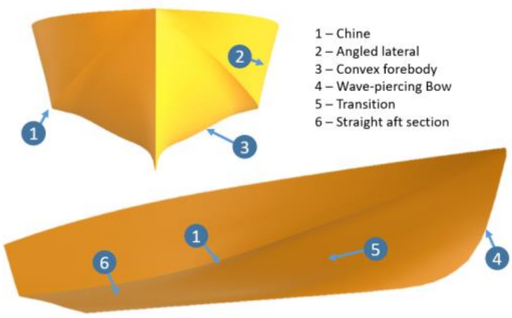

Figure 3: Refined hull shape

Hydrofoil Design

The hydrofoil design process consisted of finding the optimum combination of different background theories, calculation procedures and software packages. The foil arrangement and shape were carefully analysed in order to provide sufficient lift for the hull to take-off and be stable and efficient once foiling. In addition, the structural properties were chosen so as to achieve minimal weight yet ensure sufficient stiffness at high speeds.

Foil Design Process

To define the foil geometry parameters, an iterative process was undertaken. This involved analysing the operational requirements of the vessel and selecting appropriate foil shapes and configurations. The lift required for the foils to overcome the weight of the vessel was about 7360N. Using the velocity prediction program (VPP) (discussed later on), different chords, spans and angle of attack were systematically investigated for both types of foils in order to achieve the required lift. Additionally, size constraints, such as the hull's beam were considered. For each new design, the take-off speed was checked to be close to the desired speed of 12kts.

Foil Configuration

Hydrofoils can be fully submerged or surface-piercing. When fully submerged, they will generate a greater amount of lift, which does not change with the immersion of the craft. This adds additional complexity to its stabilisation control. Conversely, the lift produced by a surface-piercing foils will change with immersion, especially as the vessel takes off. These interactions help provide good pitch stability when manoeuvring, acting as a passive control system. For the vessel design, the fully submerged foil would provide most of the lift whilst the surface-piercing foils would act as a passive control system reducing the need for complex pitch control mechanisms.

The analysis of hydrofoil shapes was done through research and comparison of parametric designs (Figure 4). Regarding the fully submerged foils, a T-Foil and L-Foil were analysed. The primary reason for this decision as that this type of fully submerged foil could use its strut as a rudder. The T-Foil was chosen due to its strut connection being in the middle of the wing and not at the edge. For the surface-piercing foils, a J-Foil acting at an angle was used to provide roll stability.

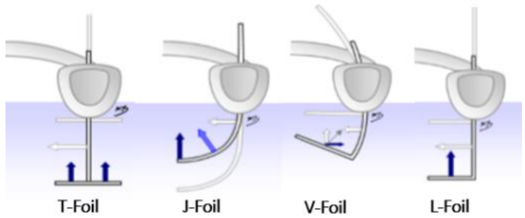

Figure 4: Different foil shapes

The final step for the foil configuration choice was to decide the foil locations. As the fully submerged foil is the vessel's rudder, it was considered to be at 0m from the stern. For the surface-piercing foils, an iterative process was used. Foil geometry, location, and moment calculations were used to find the initial ideal position of the surface-piercing foils. The foil was assumed to be fully submerged. This set the position of the surface-piercing foil at 2.7m from the stern.

Foil Section

From some initial research, a list of commonly used foil sections was compiled. From this, three asymmetric foils were chosen for further research: NACA 2412, NACA 4410 and NACA 63-412.

All foil sections were run through a preliminary hydrodynamic analysis using a panel method code. This data enabled comparison between the foil section performance and the aspect ratio. From the lift to drag ratio graph, Figure 5, it was possible to see that the NACA 2412 section is the least efficient up to 2˚ of AoA. However, a lower performance section was needed in order to facilitate the lift control once at top operational speed. In addition, from a cavitation analysis, the NACA 2412 will only start cavitating after 37 knots at the design angle of attack. Hence, the NACA 2412 section was chosen for the lifting surfaces.

A similar process was done for the hydrofoil strut. As mentioned before, it was decided that the fully submerged foil strut would work as the rudder for the craft. Hence, a section which produces the least amount of drag, no lift at zero angle of attack, and an efficient lift to drag ratio when turning the vessel would be required. After the analysis, it was decided that a NACA 63-012 section would present the best performance for the strut when at different turning angles.

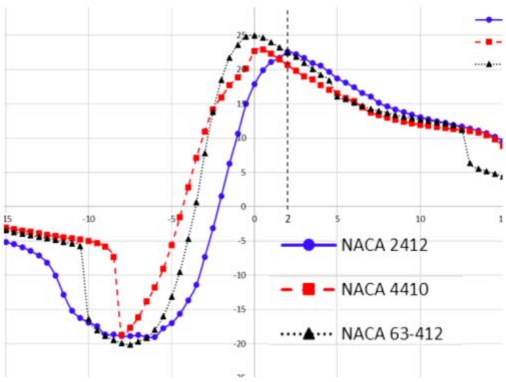

Figure 5: Lift to drag ratio at different angles of attach for different foil sections

Tapering

In order to reduce the induced drag and increase the foils' torsional stiffness, it was decided to shape the hydrofoil with a straight swept back wing and a taper ratio. The final design, using a taper ratio of 0.5, showed a decrease in drag of 30% in all foils.

Stability

The roll stability of the craft when foiling was analysed to understand whether the surface-piercing foils design would produce enough roll restoring force to counteract the roll motion caused by a steady turn. This allowed the optimum dihedral angle to be obtained.

The roll and sway restoring forces of the craft were calculated to find the heel and drift angles.

The heel angle (φ) would allow the roll motion of the vessel, described in Figure 6, to be assessed at high speeds. The drift angle, shown in Figure 7, represents how much the vessel would drift out of course when turning. Due to the uncrewed nature of the vessel understanding the course deviation and therefore, drift angle is paramount. The driving dimensions of these calculations were the dihedral angle (β) and the immersed length of the lifting surface of the surface-piercing hydrofoil when flying. A comparison between both values was conducted to find the most feasible combination possible. The ideal dihedral angles were filtered according to whether their heel and drift angles met the acceptable limits (<5˚ for heel angle and <30˚ from course for drift angle).

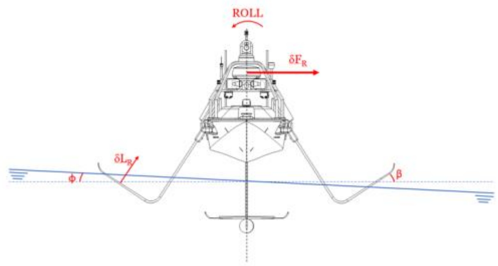

Figure 6: Roll motion force diagram

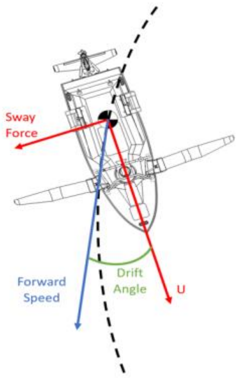

Figure 7: Turning diagram showing drift angle

The data gathered from this analysis allowed a final decision to be made on the surface-piercing foil geometry. It is important to note that the design was chosen to have outwards facing foils to give improved stability when turning. Table 3 provides the final dimensions found after the last stability iteration in this design cycle.

Table 3: Final foil dimensions

Dihedral angle	33.0	°
Strut height	0.80	m
Immersed foil span	0.73	m
Heel angle	2.24	°
Drift angle	27.0	°

Winglets

To improve the performance of the hydrofoils, the addition of winglets at the tip of the wings was considered. This feature is fairly common on aeroplanes, where it reduces the induced drag by 20% and increases the lift to drag ratio by approximately 10% at high speeds. In water, winglets still produced an increase in efficiency of the foil by reducing the wingtip vortices. To thoroughly analyse these effects, a practical test or use of CFD is needed, as a small change in geometry can create an inefficient feature. Due to the lack of access to computing power when working remotely as consequence of the COVID-19 pandemic, this CFD analysis was not possible; however, it was decided to use winglets due to the efficiency gains that had been achieved in other studies, with the understanding that this would require further work to confirm.

Lift and Drag Predictions

The lift and drag could be predicted using the VPP developed throughout the project (see later). As it is possible to see from Figure 8, there is a region of instability close to the take-off region. This is due to the code trying to simulate the trim control and, when the vessel is about to take-off, a region of instability occurs before the craft is fully flying. Therefore, it is estimated that the take-off speed is in the range of 12 knots, as observed from the red dashed trendline on the graph. Drag of the foils was also estimated to present a maximum value of about 120N, as seen in Figure 9.

Material Choice

To help with the materials choice for the hydrofoils, the software package CompoSide from the company StrucTeam was used. The minimum stiffnesses for each foil component (including the strut) was calculated so as to have a maximum tip deflection of 5% of its span. Carbon fibre, glass fibre, stainless steel and aluminium were analysed together with PVC and PET foams for the core. To save weight and meet the stiffness criteria, various materials were tested in an iterative way. The configuration chosen was of a standard modulus carbon fibre structure with a PVC foam core of 0.2m chord. The T-Foil strut analysis incorporated the fact that that a cable of 1cm diameter would need to go down through its inside to carry the propulsive power. According to CompoSide, the hole diameter needs to be less than half of the thickness of the foil (in that case, core), and this requirement was met. The carbon fibre would be laid up with stacks of 5 unidirectional layers separated by 1 biaxial layer of 45˚. This technique, known as interleaving, avoids interlaminar failure issues. An FEA analysis was conducted on the hydrofoils which showed the surface-piercing foils reached a deflection of 1.95% of its span, the T-Foil strut reached 4.54%, and the T-Foil wing reached 0.33% – all meeting the stiffness criteria.

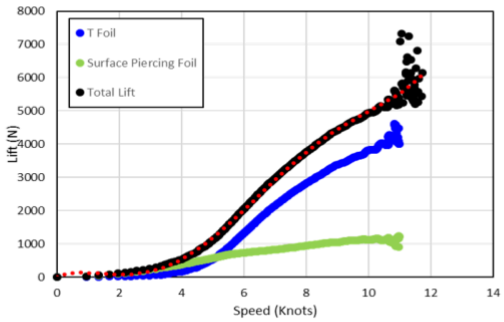

Figure 8: Foil lift for speeds up to take-off

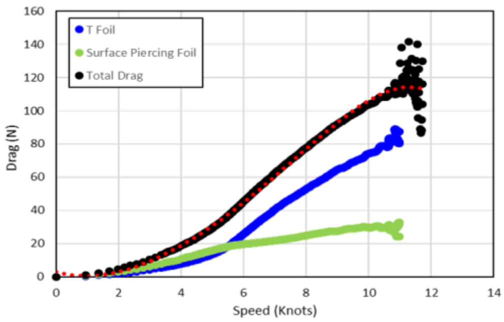

Figure 9: Foil drag for speeds up to take-off

Velocity Prediction Program

In a conventional concept design, existing design methods and empirical relationships are often used to provide useful design information with a reasonable degree of accuracy. However, these relationships do not extend to providing information on the transitions between the different modes of operation, namely displacement operation, planing, and foiling. This, combined with the fact that many of these relationships were developed for vessels larger than the one considered here and as such, did not appropriately scale, meant that an alternative approach was necessary. Therefore, a velocity prediction program (VPP) was created in Python to simulate the forces acting on the vessel and investigate what its response would be, thus enabling calculation of operational parameters. The VPP also incorporated lift and drag calculations for the foils, thus allowing the VPP to be used to dimension the foils. Due to the forward and vertical motions at play here, as well as to keep the VPP within a reasonable scope, the VPP was limited to a surge-heave-pitch analysis.

Methodology

The VPP was approached with an object-oriented coding and making extensive use of classes. This allowed an object to be created for the hull and for each foil within which all the object information and functions were stored. In all cases, the code was written to be as flexible as possible, meaning that any size vessel with any foil configuration could be analysed.

Hull Import

The hull shape was designed in Maxsurf hull modeller software. To allow for easy compatibility, the VPP was designed to read and import an LFH file, which is easily exported from Maxsurf. An LFH file contains coordinates of the hull surface at a number of sections along the vessel's length. For each section, functions were written to calculate the waterline offset, immersed sectional area, or the length of the immersed part of the section – all at any given draught. The imported hullform is plotted in Figure 10.

Use of longitudinal integration of the sectional properties then allowed functions to be written that calculated the immersed hull volume, waterplane areas, and wetted lengths.

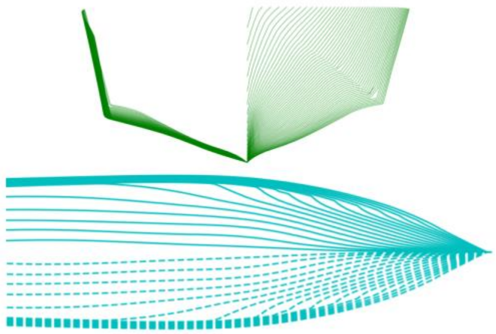

Figure 10: Hull imported into VPP

Hull Force Calculation

The most challenging of the forces to evaluate was the resistance, as there are many equations for the resistance in the different speed regimes of the vessel, but these do not often blend together well. Therefore, some relevant experimental results were used to create a resistance profile that scales up to any specified scale. Outside the range of scaled testing velocities, the ITTC ‘57 frictional resistance was used for slower speeds and the theoretical Savitsky’s planing equations were used for the faster ones. This resulted in a smoother and better-behaved overall resistance profile. The remaining forces, namely buoyancy, normal force, weight and air resistance, were all calculated using standard theoretical equations.

Foil Setup

The vessel uses two different types of foil, meaning two different classes were created: “T_Foil” – for the aft foil and “J_Foil”- for the forward foils. The primary purpose of these was to be able to call lift and drag methods on both of them, with all the unique aspects of each foil being handled by the class and its associated methods. Each foil object was given an associated longitudinal position and stored its dimensions.

From these, a number of calculation functions could be written to obtain important geometrical parameters of the foils – in particular the frontal areas of both the foils and their struts, as well as each foil’s immersed volume. In addition, functions to calculate C_L and C_D for a specified trim angle were added. In the case of the J-Foil, this was complicated by a change in trim not resulting in an identical change in angle of attack. Therefore, an additional function to transform the geometry using coordinate transformation matrices was added which allowed calculation of the rotated flow velocities and relevant angles of attack.

Foil Force Calculation

Having already implemented the required functions to obtain velocities, angles of attack, and lift and drag coefficients, the calculation of the forces was a relatively simple affair of combining these values in standard lift and drag force formulae.

Force And Moment Resolution

A free body diagram of the vessel and the forces acting on it is shown in Figure 11. With all these forces calculated, any that were in the body-oriented axes as a result of a trim angle were resolved into the global axes, allowing for calculation of a net horizontal and vertical force. In addition, the points of action of each force were calculated and moments were taken about the zero point.

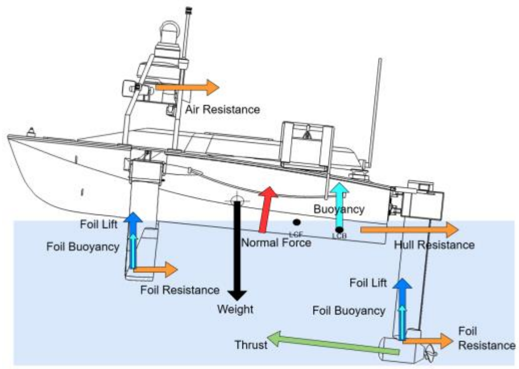

Figure 11: Vessel free body diagram

Control

To simulate the type of responses that would be required of any control systems, as well as to maintain a level of control on the simulation, PID control of the trim angle, trim velocity, ride height, and thrust were implemented. The thrust PID response was calculated based on a target speed and simply varied the thrust of the motor, whereas the trim and ride height control mechanisms achieved a response by varying the angle attack of the rear T-foil.

Simulation

Combining the steps above allowed for solving the forward and vertical equations of motion, as well as the trim-based rotational equation of motion, provided it was over a small time-step which would result in a small change in velocity and position. The new state of the vessel calculated by these equations after the passage of one time-step could be fed back into the equations to solve for the next time-step, thus simulating the motion. This particular VPP functioned by taking a target velocity as an input, with desired ride height and trim angle as optional inputs and running the simulation over a specified length of time with a specified time-step. From this data, the steady-state of the vessel can be obtained, as well as its behaviour when accelerating.

VALIDATION

Many of the underlying calculations, such as the hull geometry, area, and volume calculations were validated by comparing results with outputs from MAXSURF Modeler and ensuring they were within a reasonable tolerance. The remaining functions were all validated using appropriate hand calculations.

RESULTS

The simulation results provided by the VPP were encouraging. An initial simulation of the static condition with no forward velocity was performed to assess the static draught and trim. The results of the iterative simulation showed the vessel's draught and trim settling to a stable value, which was very close to the predicted static draught and trim thus, validating the vertical force and moment calculations.

Applying a thrust force and simulating the forward velocity gave very useful results regarding the trim and draught changes involved as the vessel accelerates. Also of note are the resistance calculations which show the resistance increasing with the velocity until enough lift is generated to start significantly lifting the hull out of the water, at which point the resistance begins to decrease despite the increase in velocity. This is expected with foiling craft and was another reassuring result to find.

Unfortunately, beyond the point off take-off, as would be the case with any foiling craft, the vessel became a lot more sensitive to changes in trim and ride height. This meant that it did not become possible to stabilise the vessel after take-off to obtain data for a fully unconstrained model. However, if the assumption was made that appropriate control systems would ensure the vessel would remain at a fixed ride height or a fixed trim, the VPP supported the full range of speeds and behaviours from static to fully foiling. From this data, resistance estimates for the vessel when at constant full speed or slower could be made, providing essential information for calculating the powering requirements of the vessel. Figure 12 and Figure 13 show some key results for the unconstrained pre-take-off stage that was stable.

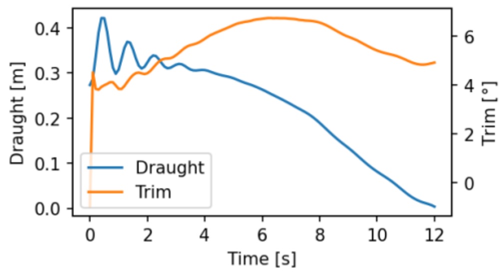

Figure 12: Draught and trim as vessel accelerates

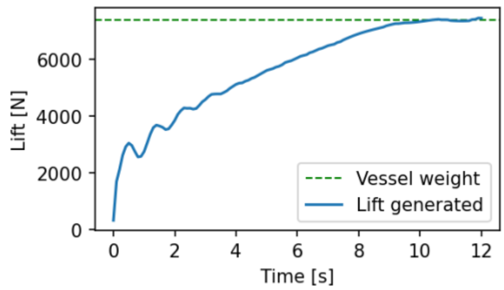

Figure 13: Lift generated during vessel acceleration

FINAL DESIGN

Overview

The final vessel design is seen in Figure 14, and the particulars of the final design are given in Table 4. The operating procedure of C-Flyer is as follows:

1. Coastguard is alerted to an incident and C-Flyer is launched under the command of a remote operator.
2. C-Flyer reaches operational speed and foils to the appropriate area, using sensors to commence a search if necessary.

3. As C-Flyer approaches the casualty, the speed is reduced, and the foils retract to enter displacement mode.
4. Onboard-communication systems allow for communication with the casualty and C-Flyer can deploy a liferaft and act as a beacon for other search and rescue vessels. When these vessels arrive, C-Flyer cay stay alongside the casualty, if necessary, for illumination or communication.
5. C-Flyer return to base for refuelling and maintenance.

Figure 14: Final vessel design

Table 4: Final vessel parameters

Length Overall	4.8	m
Length BP	4.05	m
Width (foils deployed)	5.4	m
Beam	1.35	m
Draft (amidships)	0.35	m
Displacement	750	kg
Height (bottom of foil to top of mast)	3.45	m
Endurance	3.5	hrs
Range	80	nm
Top Speed	37.5	kts
Design Speed	35	kts
Payload	2x Liferaft + equip. **or** 75kg	

Modes of Operation

The hydrofoils on C-Flyer are able to retract to remove them from the water when in displacement mode. For the surface-piercing foils, hydraulic systems are used to pivot the blades around the attachment point on the hull. The foils fold up and are held either side of the main mast. The rear T-foil is lifted vertically on a rack and pinion device. This allows the motor to stay in the water and continue to provide thrust.

The displacement mode allows C-Flyer to approach casualties that are in the water in a safe manner without injuring them. Furthermore, C-Flyer has a smaller beam extent when in displacement mode allowing other craft to get alongside easier. Retracting the foils also reduces the resistance when the craft is travelling at lower speeds which is important to conserve energy. When C-Flyer is ready to start cruising, the foils are lowered into the water with the hydraulics. The vessel accelerates and the foils allow C-Flyer to operate at a designed cruising speed of 37kts.

Range

The designed endurance of C-Flyer at its top speed is 1 hour. This has been chosen as it is roughly 70% of the energy available. With the remaining energy, C-Flyer would operate at a lower foiling speed, as a lower speed results in greater range. 18kts was selected as this lower foiling speed as an acceptable compromise between speed and range. This economic use of the speeds will allow C-Flyer to successfully operate as a first responder.

Operating Sea States

The maximum distance the C-flyer could travel from the English coastline was 12nm, within the territorial sea. Wave buoy data, detailing wave height and zero crossing period, was averaged along a line 12nm from the South Coast. This enabled an operating range of sea states for the C-Flyer to be established representing 80% of these wave conditions. This was later refined to 70% after simulating these conditions and establishing a maximum operating wave height of 2.5m.

Power and Propulsion

The powering system of the ASV must be able to provide sufficient energy to both propel the vessel and supply the hotel powering requirements. This includes electronics such as the communication and navigation equipment, the control system motors and actuators, and the casualty detection sensors, amongst others. The propulsion must: be lightweight to minimise the size of the vessel; provide large amounts of energy readily; be easy and cheap to maintain; and be sustainable and not contribute negatively to the environment.

C-Flyer is hydrogen-powered. Hydrogen systems are beneficial due to their relatively low cost and light weight. They also produce zero emissions during use. The power plant is all enclosed within one system - the fuel cell.

The key drawback to a hydrogen system is the lack of national infrastructure. This means it is more difficult to acquire hydrogen compared to fuels such as diesel. However, the fuel is available from suppliers in standard size cylinders which, while slightly more difficult to procure, benefit from the sustainability of the option [14]. Hydrogen has already been used to power buses, demonstrating the applicability of hydrogen as a power source. Another benefit is that, due to the fuel being a gas, it has a very low weight. Therefore the difference between full tanks and empty is minimal – this leads to it being easier to maintain a good flying ability throughout.

Propeller and Motor Selection

Using the resistance predicted for the cruising speed of the ASV, a propeller can be designed, and a motor can be selected. The propeller was designed from the Wageningen B-Series because of the wide availability of the K_T, K_Q and l efficiency curves [15].

From the propeller design, it was likely that the motor would need to provide a relatively high torque and high RPM. The motor should also be as light and as small as possible as it was to be located in a pod below the T-foil to minimise drag. An AC-09 induction motor was chosen, due to its relative low voltage and its ability to provide the required RPM and torque.

The Burrill and Emerson approach was used to assess the cavitation characteristics of the propeller. The design line used is typically for warships and other fast craft and is therefore appropriate for the ASV [15]. Using this design process, the propeller detailed in Table 5 was generated.

Table 5: Propeller properties

Design BAR		1.050
Required BAR		1.010
P/D		1.002
Propeller Diameter (m)		0.2
At the Design Speed	RPM	7000
	Torque (Nm)	92.57
	Propeller Efficiency	0.565

The required torque for the design speed is lower than the rated torque of the motor and the RPM is also lower than the maximum RPM. This allows the vessel to reach the design speed when the resistance increases such as through fouling or inclement weather.

Hotel Loads

To assess the total power required by the vessel, the hotel loads had to be analysed. The power requirement for each component was calculated, and then summed together. The total was multiplied by a safety factor of 1.5. This ensured a margin for any components that had been overlooked and that the crafts powering requirements were met as, it would be a serious failure if the ASV lost power during a mission. The total hotel load calculated was to be 1.19kW.

Emergency Batteries

To provide back-up power, it was decided that a battery should be on-board for use in emergencies. This would be used in the circumstance where the hydrogen system failed or ran out of fuel. A 190Ah 12V battery was selected as this allowed the ASV to move at 5kts and operate its other systems for up to an hour. This would allow the craft to begin travelling towards its base or away from treacherous areas such as shipping lanes. During operation the battery would be recharged by the fuel cells.

Fuel Cell Selection

The largest power requirement would be when the ASV is foiling at its cruise speed of 35kts because, this is both the largest resistance and the largest velocity of the craft. An effective power of 28kW will be required to be produced at this speed. Due to the inefficiencies of the entire propulsion system and the hotel load requirement, an installed power of 36kW is required [15]. Furthermore, a 20% safety factor has been added to ensure that enough current is generated during accelerations and other high loading scenarios. This gives a total of 43.4kW of installed power. Hydrogenics fuel cells were selected to provide the powering as they are already being used on commuter trains and buses – meaning they are safe and reliable to use. They are also advertised as being “robust, rugged and reliable” and compact in size which is perfect for the ASV. Several arrangements of fuel cell were assessed to provide the required power, and the arrangement with the lowest weight was selected. Two fuel cells would be required: an HD 15 and an HD 30. These are detailed in Table 6. During operation, the smaller fuel cell would be used for low speeds, then the larger fuel cell for greater power requirements and then both would be combined for the highest speeds [14].

Table 6: Chosen fuel cell properties

Type	Continuous Power (kW)	Mass (kg)
HD 15	16.5	55
HD 30	31.0	75
Total	**47.5**	**130**

HYDROGEN REQUIREMENTS

Due to the lack of hydrogen industry in the UK, it has been decided that standard size hydrogen cylinders should be used. This allows for the easy restocking of supplies and lifeboat crews only have to operate one type of system. If the ASV was designed to always be foiling at its top speed, the craft would require 2.30kg of hydrogen. This would require four of the standard size hydrogen cylinders which would have a very large volume requirement. Furthermore, there is no need to be travelling at top speed on the return trip from an incident. Therefore, to enable the system to run on two cylinders, the ASV would travel at its top foiling speed (35kts) for one hour. This equates to 70% of the available energy. With the other 30%, C-Flyer can foil at 18.25kts for the return journey. This allows the craft to still be foiling but the decreased power requirement means it can last for an additional 2.4hrs. This will still allow the craft to get out to incidents at top speeds but is more economical for the return journey.

FINAL DESIGN SUMMARY

Figure 15 shows a render of the major powering and propulsion systems. The system is powered by two hydrogen cylinders and two fuel cells which generate the electricity needed to operate the hotel loads and the podded motor for the propulsion. The cylinders slide into the craft from a door in the transom and are manually connected. A battery provides backup power in the case of failure of the main system. The propeller has been designed to power the craft to 37.5kts which is faster than current RNLI lifeboats meaning that the ASV would be able to act as a first responder.

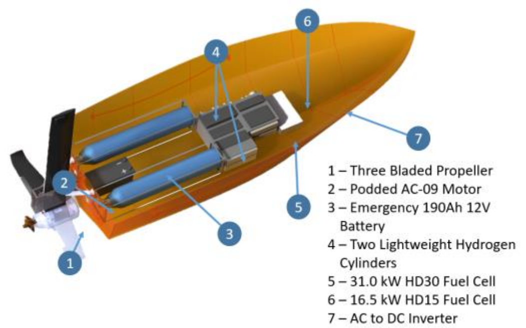

Figure 15: Powering and propulsion arrangement

Structure

The material and structural arrangement was designed such that it could withstand the maximum local and global loading conditions it is subjected to, both in terms of yield strength and fatigue life. In addition, the structural weight was minimised where possible, whilst considering the sustainability and maintenance requirements of the hull.

The starting point for the structure design was to research the regulations appliable to the 4m long autonomous rescue vessel. The MCA rescue boat code requires vessels to be built to ISO standards [16]. This includes the ISO standard 12215, Part 5 which provides regulations for panel pressures and minimum thicknesses [17]. These are mostly based on empirical deduction of previous designs, however, provide a solid framework early in the design process. The ISO standards gave a minimum starting point for the material development and prevented drastic adjustments mid-way through the project.

The Wolfson Unit's software Hull Scant was used to assess the initial structural arrangement and GRP composite selection against these regulations. This software should not be used in isolation to assess the structure due to the negation of the local foil forces; these were computed using the VPP. The specific wave conditions for the vessels region of operation were also found using Ansys Aqwa. These other load cases were analysed using FEA.

Wave Loading Analysis

The wave pressures acting on the hull were computed by modelling the vessel in Ansys Aqwa. Assuming a forward speed of 15knots and that the vessel was fully displaced. A range of sea states given in Table 7 were applied reflecting the 80% of the English Channel sea states the vessel was designed to operate in [18].

Table 7: Sea states analysed in Ansys Aqwa

Wave Period (s)	Wave Frequency (rad/s)	**Sea States Tested**	**Finalised Sea States**
		% Sea State Represented	% Sea State Represented
2.5	2.51	3.8	3.8
3.5	1.80	15.6	15.6
4.5	1.40	18.1	11.8
5.5	1.14	16.1	16.1
6.5	0.97	9.9	7.3
7.5	0.84	6.7	5.2
8.5	0.74	2.9	2.9
9.5	0.66	3.2	3.2
10.5	0.60	3.2	3.2
11.5	0.55	2.5	2.5
Totals		**82**	**71.5**

Global Structural Loads

The maximum wave pressure, calculated earlier, was applied non-uniformly over the hull bottom with the highest pressure at the bow. Transverses were installed at the bow and aft of the surface-piercing foil retraction system to reduce the stress concentrations observed on the bottom of the hull when subjected to the maximum wave condition. The stresses reduced the fatigue life of the hull to 0.5 million cycles. From the sea state analysis this loading condition represents 15.6% of the total states the vessel would encounter thus, over its lifetime the vessel may observe an order of 0.5 million wave cycles. The reduction in stress concentration and consequent improvement in fatigue life by installing these transverses is shown in Figure 16.

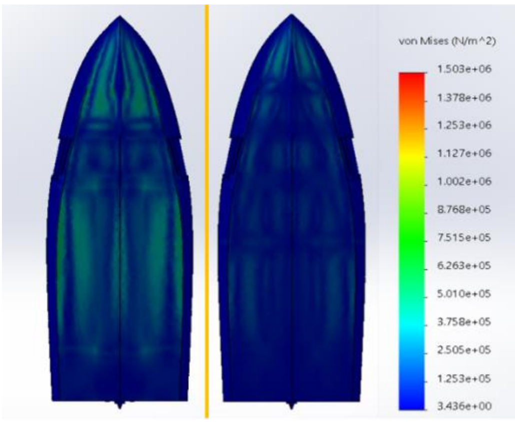

Figure 16: Before (left) and after (right) comparison of transverse installation

The final global condition considered under normal operation was the vessel slamming out of foiling mode. In this case the weight of the vessel acts uniformly over the hull bottom exerting a pressure of 1350Pa. A transverse was installed further aft of the surface-piercing foil retraction system to reduce stress and improve the fatigue life of the hull bottom under this condition.

Foil Attachment

The foil attachments were assessed as local loads under the worst-case loading condition, when the vessel travels at its maximum speed (37 knots). It was assumed the foil lifts were controlled above the take off speed. The lift and drag of the foils were applied as remote loads shown in Figure 39. The attachments themselves were assessed for yield and fatigue. The stresses acting on the hull from the attachments were then applied in the second stage of the FEA analysis. The hull design was then optimised to prevent yield or fatigue and to better distribute these stresses.

The force on the hull from the attachment initially caused the hull to yield, as shown in Figure 17. Stainless steel inserts were used to stiffen the hull in this area, and the supports were also thickened to transfer the stress to the transverse structure. This reduced the stress concentration to a maximum of 67MPa, well below the yield stress of 304 stainless steel (290MPa).

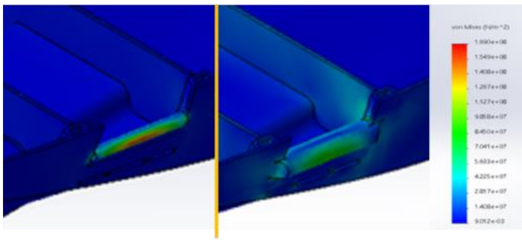

Figure 17: Before (left) and after (right) attachment point optimisation

The T-foil attachments will be manufactured from 304 stainless Steel. After applying the stress exerted by the attachment to the hull it was evident that the hull would yield at a stress of 20.4MPa, shown in Figure 18. To prevent this, two longitudinals were installed beneath the hydrogen cylinders and a central longitudinal girder to transfer the load from the transom. These longitudinals also provide a support for the mid-deck deck. Furthermore, the edges of the hatches for the Hydrogen cylinders were rounded to prevent stress concentrations in these areas. After this optimisation process, the stress in the transom reduced from 36MPa to 9MPa.

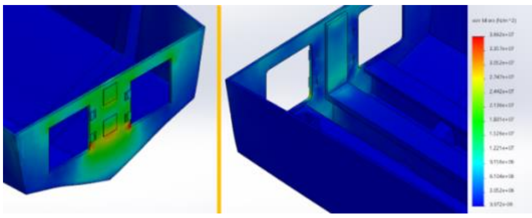

Figure 18: Before (left) and after (right) transom optimisation

Outfit

C-Flyer has been designed specifically for search and rescue. Lightweight components with low power requirements have been chosen to enable maximum capability. Items such as the main camera have been chosen due to their advanced technology. Cost has been viewed as a design factor; however, it has been considered as not limiting to the development of C-Flyer, as this allows the final design to have the most advanced capabilities possible. However, other alternatives of many of the components are available.

Payload and Modularity

The usefulness of this design is based around its capability to get to a desired location quickly and assist a person in distress. Due to the unmanned characteristics of this vessel, the assistance provided is limited in its form and flexibility. As a result, the payload for a search and rescue operation was design with two main concepts in mind: immediate support and remote assessment. Upon arrival at the causality, the operator is informed of such and can perform the first visual assessment via a multitude of cameras onboard. The loudspeakers and microphone also enable two-way communication for a better assessment. Based on this assessment, the operator may choose to launch the liferafts or not. Even with the liferaft launched the operator will maintain contact with the causality to gather as much information as possible on the victim's condition, thus improving the response once the manned craft arrives.

The craft is equipped with 2x SOS Marine two-person liferafts. Despite being designed for coastal water, the liferaft features ballast pockets, enabling sufficient stability in rougher sea states. Additionally, the liferaft is equipped with a sea anchor, knife, air pump, flares, bottled water, and thermal clothes. This is aimed at increasing the chances of survival whilst, waiting for the manned craft to arrive. The choice of having two liferafts enables for redundancy in the system and the capability to assist more than a single causality on a single launch, if required.

From the initial research, it was apparent that the industry is moving towards modular designs [5]. With the payload being roughly 10% of the displacement, various arrangements could be implemented on C-Flyer. Additionally, the different arrangements should be designed in such a way that manufacturing is straightforward. The solution was to adapt the superstructure design to the different features required and adapt the mast equipment accordingly. As a result, a single component must be changed in the manufacturing process and another on the assembly stage. Based on the case studies initially developed, three main arrangements are presented as representative of potential capabilities. These are shown in Figures 19-21, which showcase the adaptability of the design proposed for three different sectors in addition to search and rescue. It is important to note that the designs have been tested for stability to ensure its feasibility.

Figure 19: Cargo C-Flyer

Figure 20: Security and firefighting C-Flyer

Figure 21: Research C-Flyer

Launch and Recovery

The RNLI uses several methods of launch and recovery. The main methods are beach launching, slipway launching, and deployment with a crane. So that the C-Flyer can be used as a nationwide search and rescue first responder, it must be able to be launched in all these methods as quickly as possible.

To be useful, C-Flyer needs to be launched as fast as possible with the minimum number of crew operation. Where possible, this could be done remotely. This is relatively simple on a slipway or with a crane if it can be ensured that no one is in the path of the launching ASV. Furthermore, the fuel cells used to power the craft lend themselves to faster launches, as they have a start-up time of less than five seconds [14].

Remote launching is more difficult on a beach due to the requirement of some form of carriage. In an ideal situation, an automated tractor could be used to drive the ASV into the waves deep enough to allow it to float off. However, on a crowded beach this may be difficult to be achieve without an operator being present. For RNLI stations where beach launches are the norm, it may be simpler to have the ASV stationed offshore or in harbours in a standby mode ready for when an incident occurs. The battery could be used in this mode which would give over 12 hours of operating in low power mode. If this were the case, an appropriate mooring could be designed to allow the craft to stay stationary without the need of its own propulsion equipment.

Figure 22 shows the clear benefit of remote launching in comparison to a manned crew. In 2018, the average launching time for the RNLI was just over 9 minutes. In this time, a C-Flyer vessel could be up to 5.25nm away from the lifeboat station allowing for an assessment of the situation before a lifeboat is even in the water – this would help prevent false alarm situations and unnecessary launches [11].

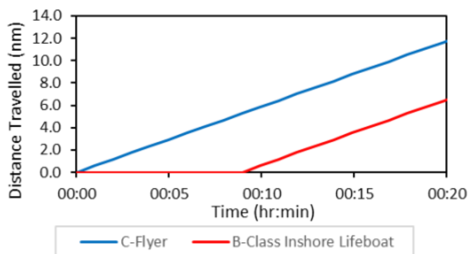

Figure 22: Response time of C-Flyer compared to RNLI inshore lifeboat

CRITICAL REVIEW

Economic Feasibility

In assessing the successfulness of the design presented, it is important to evaluate its economic feasibility. This design will not be evaluated from the perspective of making a profitable vessel but instead on the perspective or reducing or at least match current RNLI costs by considering its capital and operating expenditure.

CONSTRUCTION COSTS

The construction cost of C-Flyer varies greatly depending on the number of vessels made. A significant capital expenditure is the price of the mould. This has been estimated at roughly £14,000, which would be spread across several vessels. Furthermore, this mould cost is much less than other construction methods, such as injection moulding [19]. The other main expenditure for the construction is the rotational oven and the cooling chamber. If C-Flyer was being manufactured privately, these costs would be significant, however, dinghy manufacturing facilities could be used instead at a reduced price as relatively few units would be produced each year [20]. The price of the materials and all the components is the highest cost. This totals about £82,000 (not including the main camera).

As expected, the propulsion cost is the highest with the two fuel cells equating to over £57,500 [14]. Furthermore, as discussed in Section 4.5, the price of the camera chosen is quite substantial. The camera is priced at £160,000, but this is due to its superior capabilities. This price could be reduced by renting the system, or, if this is still costly, a less advanced model such could be used (£49,500). This choice would be down to the operator depending on their specification.

Using these costs, the total cost per vessel can be estimated at under £135,000 (using the inexpensive camera). This is believed to be a good price considering all of the capabilities of the craft, especially as the facilities cost is over-estimated and would be shared over multiple vessels.

OPERATING COSTS

The operating costs are also minimal. Each hydrogen cylinder costs £74.39, so a combined cost of £148.78 for the larger missions. Each life raft costs £767.46, but if these are recovered after use, they could be repackaged leading to some cost saving. In an event where both cylinders were depleted and both life rafts were used, the total cost would equal £1683.70. This is still considerably less than the cost for launching a RNLI boat - £5800 for an all-weather lifeboat or £2200 for an inshore lifeboat.

COST COMPARISON

If C-Flyer has ascertained that no action is needed by a lifeboat before it is launched then there is a potential saving of over £5650. It would, therefore, only require 26 occurrences of this scenario before C-Flyer has paid for its own construction costs.

Under the assumption that 40% of missions require no manned assistance, and C-Flyer was successful in preventing unnecessary launches, then C-Flyer would be economical beneficial after 67 missions total – considering the added cost of C-Flyer during manned missions.

Environmental Impact

PROPULSION

The factors that make this design sustainable are its propulsion, hull material and manufacture process. The craft's propulsion is powered by two hydrogen fuel cells. The maritime world has a severe problem with greenhouse gas emissions from ships (COx, SOx and NOx), which has led to several conventions and pieces of legislation to reduce these pollutants. Hence, the introduction of hydrogen fuel cells in a relatively small craft can show a way forward for the industry. Figure 23 shows how the hydrogen fuel cell uses hydrogen supplied from renewable energy stations (solar, wind and hydro) and how no GHG emissions are produced in the process.

END OF LIFE

The concept's hull material consisting of HDPE is another factor which contributes to the sustainability of the proposed design. HDPE at such form is completely recyclable since, after the vessel's life cycle, the hull and deck can be fully melted and reused as any type of polyethylene [21].

Although the hull is made of fully recyclable plastic, the same cannot be said about the hydrofoil's material. Plastic would not be able to withstand the stresses on the foils, therefore, stiffer carbon fibre was selected.

The disposed used carbon fibres would go through a pyrolysis process to thermally decompose the resin, allowing the fibres to be used again.

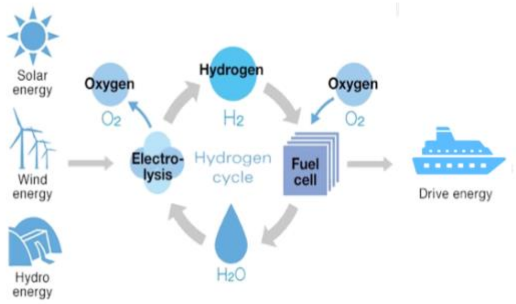

Figure 23: Hydrogen Lifecycle [22]

Legislative Framework

This section aims to contextualise current ASV regulatory framework and discuss the implementation of rules for the future. With the rise of autonomous operations in the maritime environment, operators, insurers, classification societies, and regulatory bodies felt the need to establish definitive, ASV-focused regulations. This is of importance not only in terms of safe navigation, but also to increase legal certainty in case of accident or innocent passage [23]. Currently, in the UK, any autonomous vessel that is not being used for sport or pleasure should comply with the Workboat code regarding construction [24]. However, ASV operation and normal commercial vessel operations are so fundamentally different that application of current regulations is often unsuitable. This often results in naval architects having to do extra work to provide the regulatory bodies with "equivalent means of compliance" documentation adding to the design burden [25].

Another issue with ASVs is their compliance with COLREGS. These are key for safe navigation [23] however, there is a significant amount of human judgement involved as these were originally drafted for manned operation. Amendments to this convention could include acknowledgement of ASVs and increased quantitative rules.

As a response, the IMO has included in its strategic plan for 2018-2023 the need to "integrate new and advancing technologies in the regulatory framework" [26]. Additionally, the governing body has also acknowledged that it should have a proactive and leading role in the process of regulating ASVs. Despite these efforts, the IMO has been slow and independent bodies, such as the UK Maritime Agency through its Autonomous Systems Working Group in association with the MCA, have developed codes of practise for construction standards, registration, and operation [27]. Likewise, classification societies have also developed guidelines [28]. Despite being non-prescriptive, these initiatives have shed a light to the likely end of the grey regulatory area in ASV construction and operation.

Recommendations

If given the opportunity to develop the project further the following would be undertaken on each of the key design elements.

Velocity Prediction Program

By far the most significant improvement that could be made on the VPP would be stabilising the post-take-off motion. This would most likely be achieved by further developing the PID controllers to have different control constants depending on which mode the vessel is operating in (displacement, planing, or foiling). This is because the response characteristics for each mode are quite different meaning a one-size-fits-all approach is not appropriate and will not be stable for all modes. In addition, gathering more experimental data on how the vessel's resistance changes with trim would improve both the velocity and trim calculations. Finally, at present, the blending of resistances between the experimental resistance values and theoretical ones is quite coarse, and can result in some sharp changes, leading to instability. Further improvement of these calculations could more smoothly blend the two together, thus resulting in a more stable response.

Foils

The use of CFD to predict both the free surface effects on the surface-piercing hydrofoils and the winglet geometry effects on tip vortices would have improved the foil design process. In addition, towing tank tests on scale foil prototypes used in the concept, would help validate the final design decisions. With the manufacture of scaled models of both T-Foil and forward foils, it would have been possible to more accurately predict the performance of such designs through test results.

Propulsion

The powering and propulsion of the concept design could be improved by further work on the resistance prediction. This could either be done by increased work on the VPP resistance prediction or model tests. With an improved resistance prediction, items such as the propeller could be more accurately designed, and an improved final hydrogen requirement could be calculated.

Structures

If FEA analysis could be undertaken on further systems, such as the interaction between the steering hydraulic and the transom. However, for the purposes of this project the only most critical failure points were identified, namely how the large foil forces were dissipated throughout the hull. The same analysis process developed in this project could be applied to these additional systems.

The accuracy of the fatigue life and stress predictions could have been improved in two ways. Firstly, the load cases could have been further refined, using sensors attached to the bow of a scale model the pressures of wave loads could have been measured and compared to the Ansys Aqwa simulation. In addition, the properties of a sample of the hull material could have been tested to more accurately predict the yield stress and fatigue life of the hull. This was deemed beyond the scope of this project where the aim of the FEA was to identify key failure areas and provide some reinforcements to minimise these.

Stability

The analysis of the hydrofoils' performance at different sea states would have been beneficial for the stability stage of the design. This could have been achieved on the further development of the VPP, with an incorporated function, or, again, with the use of CFD simulations.

Hull

It is believed that the design would benefit from extra internal space. The hull could be redesigned to have a less steep V-profile in order to increase the amount of usable internal space. Additionally, the hull dimensions could be slightly increased for the same reason.

CONCLUSIONS

This report details the design process followed to develop a novel vessel class for search and rescue scenarios. In summary, the proposed design is a first responder to be used for search and rescue. The vessel is not meant to replace current rescue services, such as the RNLI, but instead work alongside the current fleet to reduce operational cost, de-risk missions, and save lives. Finally, wider modularity was considered so that the vessel could be used in different scenarios without many alterations.

To design the vessel, the regular process was followed including an initial design, followed by a model scale demonstrator and a final design informed by all previous stages. To confidently present this concept design, a range of design tools were utilised, such as FEA, panel method codes and velocity prediction programs. Emphasis should be given to the purposely built VPP, as commercial software is not available for foiling-planing crafts. This program enabled the team to assertively dimension foils, predict the vessel resistance and estimate the take-off speed. The demonstrator also proved to be an essential process in understanding the issues with manufacturing and realising design flaws. Additionally, this enabled for greater degree of certainty to be achieved in our final design as the demonstrator was designed with the same tools.

The concept design is believed to fulfil the requirements set in the design brief.

Consideration has been paid to the structures, foils, and propulsion. The structural arrangement was designed to safely withstand expected worst loads, the foils are able to lift the hull out of the water and reduce the required power to quickly reach a casualty. The propulsion system was dimensioned to enable full operation in UK territorial waters and beyond if necessary. An important feature of our design is that its launch and recovery requirements can be fulfilled by current RNLI lifeboat station. As a consequence, a smoother entry to service could be achieved. Regarding the C-Flyer's economic feasibility, the business case suggests that entry to service would slightly increase capital costs but have a major benefit in terms of operational costs. This would mainly be due to reduction in the number of launches for larger, more powerful, manned crafts. Finally, the expected 60kg payload and the modularity of the buoyant box enables this design to be adapted to different operations such as rapid environmental assessment. The wider context was also considered by evaluating the environmental impact, maintenance, failure modes and the legislative background.

The major downsides to this design lie within the regulatory framework. Currently, ASVs are somewhat under regulated and may carry with them a negative connotation. Additionally, the novel propulsion system of this design may be considered simultaneously a selling point and a risk. On the one hand, fuel cell systems are well-known for their zero-emissions properties. However, on the other hand they are still not widespread, especially in the marine environment. Despite this, it is noted that ASV regulations should be significantly improved in the upcoming years and that the benefits of the hydrogen fuel outweigh its potential shortcomings.

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