Decavitator Human-Powered Hydrofoil

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Abstract

The *Decavitator* is a human-powered hydrofoil water vehicle designed for the fastest-possible speed over short distances. Since 1988, numerous versions of the underwater hydrofoil system, control and stability system, and pontoons were built and tested. In its present configuration, the vehicle consists of two kayak-type pontoons, with a central frame supporting the rider and the large air propeller. Two underwater hydrofoil wings are positioned directly under the rider. The vehicle has three operating modes: on the hulls, on two wings, or on one wing. In the fastest one-wing mode, the *Decavitator* in October 1991 set an official speed record (pending ratification) of 18.50 knots / 9.53 m/s over a 100-meter course, with an unofficial 19.59 knots / 10.08 m/s being the fastest measured speed to date. This article will outline the technical features and design philosophy of the latest version of the vehicle.

Introduction

The recent surge of activity in the development of human-powered watercraft has been sparked largely by the sanctioning of the relatively unrestricted watercraft category by the IHPVA. The novel *Flying Fish* [1] and the *Hydroped* [2] hydrofoil vehicles have substantially exceeded the performance of traditional rowed racing shells, whose development has largely reached a plateau. The race to develop the fastest water vehicle has further intensified since the announcement of the $ 25 000 DuPont Watercraft Speed Prize [3], which will be awarded to the first vehicle to exceed 20 knots / 10.29 m/s, or, to the record holder if the prize remains unclaimed after 1992.

The *Decavitator* human-powered water vehicle, shown in Figures 1 and 2, was designed expressly for the fastest-possible speed over short distances. It consists of two lightweight 17-ft / 5.2-m kayak-type hulls between which a frame supporting the recumbent rider and the large air propeller are placed. Two underwater wings (hydrofoils) are positioned under the rider via thin vertical struts. The smaller of the two wings is positioned beneath the larger wing. In addition, a small "canard" trim surface and small rudder arranged in an inverted-T are mounted at the front tip of each pontoon, similar to the systems employed by the *Hydroped* and *Flying Fish* vehicles. A surface-following skimmer controls the angle of attack of each trim surface, passively controlling the depth of each pontoon bow and thus giving roll stability. The rider controls the front rudders via a right sidestick, providing directional control. The sidestick also actuates larger rear rudders which work only when on the pontoons. The rider controls the wing submergence depth via a left lever.

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Operation

The *Decavitator* has three basic modes of operation.

Low speed. Initially, the vehicle floats on the pontoons like a normal displacement boat. The propeller is relatively inefficient at these low speeds, and the maximum speed attainable in this mode is about 8 knots (4 m/s).

High speed. The initial foil-borne mode is entered by setting the two wings at their maximum lift angle and increasing the speed to about 7–8 knots / 3.5–4 m/s (with a 140-lb / 64-kg rider). As the wings gradually lift the pontoons out of the water, the drag drops and the speed further increases, eventually allowing the pontoons to be lifted entirely clear. The low-drag pontoons and the high aspect ratios of the wings give a very shallow "power hump", so that the transition requires only a modest anaerobic effort for a few seconds. Once flying on the hydrofoils, the vehicle can be sustained by a fit cyclist at 9–10 knots / 4.5–5 m/s with aerobic power levels. A maximum effort produces about 15 knots (7.5 m/s).

Very High Speed. After unlocking a safety latch, the rider has the option to pivot the large wing up and out of the water, much like on one of the more recent *Hydroped* variants. The wing pivoting is accomplished by accelerating the vehicle to at least 14 knots / 7 m/s (a fairly hard effort), and then suddenly increasing the angle of attack of the entire wing system via the left lever, which drives the vehicle upwards. When the upper large wing breaks the water surface, rubber cords pivot it together with its mounting struts forward and up into a streamlined receptacle. The sequence is shown in Figure 3. If the high power is sustained, the vehicle then rapidly accelerates on the remaining small wing to its maximum speed. The air propeller becomes very efficient in this operating mode.

Pontoons

Each 17-foot / 5.2-m pontoon hull is shaped like a modern open-water women's racing kayak, with the deck lowered by about 2 inches / 50 mm. A similar design is employed for the monohull *Hydroped* vehicle. Molded composite construction with a hard gelcoat finish gives very nearly the lowest drag attainable. Although such exotic pontoons might seem frivolous on a hydrofoil boat, their low drag is in fact crucial to the top-speed capability of the vehicle. Reducing pontoon drag permits higher takeoff speeds, which in turn permit smaller wings and higher maximum speeds.

Higher takeoff speeds also have the important effect of reducing wave drag associated with the two-dimensional wave train set up behind a lifting airfoil. This is quite independent of the "inverse ground effect" mechanism of the free surface which increases the induced drag of a 3-D lifting wing. As described in Hoerner [4], the 2-D wave drag scales inversely with the square of the chord-based Froude number and exponentially with the square of the depth-based Froude number: $C_{D_{\text{wave}}}/C_L^2 \simeq 0.5\,gc/V^2 \exp(-2gh/V^2)$. This drag can dominate the overall vehicle drag if large-chord wings are used at low takeoff speeds. An earlier version of the *Decavitator* had a rather large takeoff wing of 5 in / 125 mm average chord, and required excessive takeoff power due to the 2-D wave drag mechanism — as clearly evidenced by the dramatic wave train set up behind the wing. Reducing the wing area by nearly half gave a larger Froude number, and produced a large power reduction despite the larger takeoff speed.

A further advantage of higher takeoff speeds is that it permits optimizing the propeller for higher maximum speeds. One useful feature of a racing-kayak hull shape is that it retains its low-drag characteristics when partially raised out of the water. This permits a very gradual and low-power transition to the foil-borne mode, where the wings gradually lift the pontoons as the speed is increased. The use of a rider-adjustable angle of attack of the wings is also important, as it permits the pontoons to remain at a nearly-level, low-drag orientation at all speeds.

Drive System

The rider is seated in a semi-recumbent position on an adjustable seat with Kevlar cloth webbing. The pedals are linked to the two-bladed 10-ft / 3-m diameter air prop via a 1/4-in / 6-mm pitch stainless-steel chain-drive with a 2:1 gear ratio. The propeller is of a minimum-induced-loss type, and has been designed with algorithms similar to those of Larrabee [5]. The propeller is designed to rotate at 250 rpm (125 rpm at the pedals) with maximum power at 20 knots / 10 m/s. Its pitch can be dock-adjusted to optimize its performance at lower speeds and power levels, and to compensate for wind direction.

If the air/water density ratio is accounted for, the 10-ft / 3-m air propeller is equivalent to a 4-in / 100-mm diameter water prop in terms of the non-dimensional thrust coefficient $T_c = 2T/\rho V^2 \pi R^2$, which determines the induced or "slip" losses. At low takeoff speeds, the 10-ft air prop gives high disk loadings (large T_c) and poor efficiency relative to what could be obtained with an effectively larger 8-in / 200-mm water prop, say. At speeds close to 20 knots, however, T_c becomes sufficiently small to give efficiencies close to 90% even at maximum power. This high efficiency is also due to the prop blade lift coefficients being reasonably high at $C_L \simeq 0.6$ (the Daedalus prop airfoil is used), so that the blade-profile lift-to-drag ratios are fairly good. Ordinarily, a substantial blade C_L at high speeds result in a very large blade C_L at lower speeds, stalling the blades and making transition to the hydrofoils difficult. However, because of the high disk loading, the prop has a very substantial self-induction, or "slip", at low speeds (i.e. it draws air into itself). Together with the modest takeoff-power requirements of the low-drag pontoons, this self-induction is sufficient to prevent the blades from stalling above speeds of 5–8 knots / 2.5–4 m/s, depending on the geometric pitch setting.

Another very large advantage offered by the air propeller is that the wing struts do not need to enclose any drive system, and can be sized as small as material-stress and buckling limitations permit. Where it attaches to the small wing, each strut has only a 1-in / 25-mm chord and a 0.15-in / 4-mm thickness. A strut enclosing a chain or shaft transmitting 1 hp / 750 W would need to be far larger. In addition, the exposed hardware associated with an air propeller has negligible air drag, while a housing for an underwater propeller mount typically has a substantial drag penalty.

Hydrofoil/Strut System

The hydrofoil system consists of two fully-submerged high-aspect-ratio wings under the rider, and two skimmer-actuated trim surfaces on the pontoon bows. The larger 60×2.35-in / 1520×60-mm (span × mean chord) wing is placed about 6 in / 150 mm below the pontoon bottoms, and the smaller 30×1.75-in / 760×45-mm wing is placed another 6 in / 150 mm lower. Each wing is supported by two slender struts placed 26 in / 660 mm apart. The advantage of using two struts is that they do not need to carry significant bending moment, and hence can be made much smaller and have a lower overall drag than an equivalent single strut. Using two struts also greatly relieves bending moments on the wings, and permits much smaller wings to be used for a given material-stress limit.

The wings employ a custom 14%-thick airfoil which has been tailored for the operating Reynolds-number range of 150 000 – 400 000, using the design principles and numerical simulation methods employed for the Daedalus wing airfoils [6, 7]. The structural merit of the relatively thick airfoil allows smaller wing areas and less overall drag than the 10-12%-thick airfoils more commonly employed at these low Reynolds numbers. The thick airfoil also gives the rather wide usable lift-coefficient range $0.2 < C_L < 1.1$, which translates to low wing drag over a wide range of speeds. The ability of the large wing to perform well from 7 to 15 knots is particularly important for the *Decavitator* as it is brought to its maximum-speed mode.

Each of the two 9×0.85-in / 230×22-mm front trim surfaces is mounted at the bottom of a slender rudder in an inverted-T configuration. Each rudder pivots on two axes in a gimbal mounted on the pontoon bow. The pitch axis is controlled by a surface skimmer cantilevered forward from the gimbal, while the steering axis is controlled by the rider via cables linked to a right side-stick. The geometry of the skimmer/trim-surface mechanism is set up to lift the pontoon bow a few inches off the water surface at speeds over 6 knots / 3 m/s. This height is firmly maintained at all higher speeds, so that the vehicle is stabilized in depth and roll, and can pivot only in pitch about the pontoon bows. This pitching alters the wing's angle of attack relative to the water surface, so that for any given speed the boat rapidly seeks the one unique pitch attitude where the wing lift equals the vehicle weight. By altering wing angle of attack relative to the boat via the left lever, the rider can therefore precisely control the pitch attitude and hence the wing submergence depth. At low speeds, a large submergence depth is best to keep the large profile- and induced-drag contributions of the free surface in check. At high speeds, the viscous profile drag of the support struts becomes more dominant, and a very small submergence depth is optimal. The minimum workable depth is set by the need to avoid ventilating the wing by an errant wave trough. Loss of lift due to ventilation immediately drops the vehicle onto the pontoons.

The pivoting of the large wing out of the water is an essential feature of the *Decavitator's* hydrofoil system. Removal of the large wing reduces the total underwater wetted area by a factor of three, giving a roughly proportional reduction in profile drag. This is partially offset, however, by a substantial increase in the induced drag due to the loss in total loaded span. Overall, a speed increase of about three knots is realized for the same power level.

Construction

The *Decavitator* makes extensive use of structural and manufacturing technology developed at MIT in the course of numerous human-powered-aircraft projects. All underwater surfaces are made via wet lay-up of solid carbon/epoxy vacuum-bagged in female molds. The use of carbon fiber is essential since the small wing dimensions push material stresses to the limit. The small wing, for example, experiences 100 000 psi / 690 MPa material stress with a 140-lb / 64-kg rider at 2 g, and hence could not be safely built even out of aircraft-grade solid aluminum. The struts connecting the pontoons are oven-baked tubes made of pre-preg carbon fiber formed around aluminum mandrels. These are also highly stressed, and the use of carbon fiber gives greater stiffness as well as weight reductions of many pounds over equivalent aluminum tubes.

Each pontoon shell is a pre-preg glass/carbon/Nomex/glass sandwich, and was baked inside a mold for an open-water women's kayak owned by Composite Engineering of West

Concord, MA. The top of each pontoon is permanently sealed off with a glass/Nomex/glass deck. Internal plywood bulkheads hold the strut-attachment bolts.

The fuselage frame supporting the rider and drive system is constructed of thin-walled large-diameter aluminum tubes joined with Kevlar/epoxy lashings in lieu of welds. Carbon-fiber tubes were rejected for the frame from durability considerations. In retrospect, a carbon-tube frame clearly would not have survived the numerous modifications and general abuse seen by the frame over the vehicle's three-year lifetime. The seat is likewise constructed of lashed thinwall aluminum tubing with a Kevlar cloth webbing, and employs adjustable mounts for different-sized riders. The drive system employs standard bicycle cranks and pedals, lightened somewhat by drilling. The chainwheels and sprockets for the 1/4-in / 6-mm pitch chain were custom-made from high-strength 2024-T4 aluminum plate by numerically-controlled machining.

Each propeller blade is a hollow shell with a hard Rohacell-foam shear web, bonded to an aluminum-tube root stub. The shell surface is a Kevlar/Rohacell/Kevlar sandwich, laid-up wet and vacuum-bagged in a female mold. Carbon-fiber rovings are incorporated into the shell sandwich for bending strength. The propeller shaft is a thin-walled large-diameter aluminum tube.

Further Developments

Possibilities for further increasing the *Decavitator's* performance include the following.

Smaller Takeoff Wing. Since the effort required to lift the pontoons off the water is quite modest, the area of the large wing could be decreased somewhat. The areas of the front trim surfaces could be decreased proportionately as well. The reduction in wetted area would reduce the considerable effort needed to achieve sufficient speed for the transition to the single-wing mode. The rider would then have more energy available at maximum speed.

Aero Fairing. Although all major exposed tubes and struts have already been carefully faired, the aerodynamic drag near 20 knots / 10.3 m/s still consumes between 25% to 35% of the propulsive power, most of this being drag on the rider. Enclosing the rider in a high-quality aerodynamic shell would theoretically push the maximum speed past 20 knots. Naturally, for record-setting runs it is desirable to operate the vehicle with the fastest legal tailwind (3.22 knots / 1.67 m/s) to reduce the air drag to an absolute minimum.

Larger Rider. The benefits of increasing rider size on a hydrofoil vehicle are significantly smaller than on a bicycle. The actual benefits depend on the relative fractions between profile and induced drags. With the maximum legal tailwind, the *Decavitator's* induced drag is about 27% of the total at 18 knots / 9 m/s, and 20% at 20 knots / 10 m/s, so a larger rider would have some advantage. However, the vehicle's hydrofoil system is already very highly stressed with the 140-lb / 64-kg design rider weight, and a significantly heavier rider would require larger underwater surfaces to provide greater structural strength. Also, the heavier rider would need to expend disproportionately more power to lift the pontoons and when preparing for the single-wing operating mode, unless the wing areas are increased. In either case, much of the larger rider's advantage disappears.

Larger Propeller. As mentioned earlier, the air propeller is relatively inefficient at lower speeds due to excessive disk loading. Increasing the diameter would therefore give more thrust at low speeds for the same power input, giving faster transition and acceleration. This may significantly conserve the rider's energy and hence permit a higher power level to be sustained over the 100-meter course, although this is difficult to quantify. Offsetting this potential benefit is the increase in size and weight of the supporting frame, and an increase in the nose-down moment of the high thrust line. The latter must be overcome primarily by the small front trim surfaces, and these would need to be larger to avoid stalling at low speeds, which would in turn carry a drag penalty at higher speeds. Likewise, the larger prop would be more prone to blade stall at low speeds. This would require reducing the design blade lift coefficients, which in turn would reduce the blade-profile lift-to-drag ratios and lower the efficiency at maximum speeds. It appears that the tradeoffs inherent in the larger air propeller are complex enough to defy a reliable analytic optimization, and trial-and-error may be the right recourse.

Cleaner Large-Wing Configuration for Recreation. The current hydrofoil system has two separate struts on each side for the large and small wings, in order to permit the large wing to pivot out of the water. The two struts on each side are arranged one behind the other with a small gap. This produces a significant drag penalty when the vehicle is operated on both wings. For a recreational vehicle, the power levels in this mode could be significantly reduced by removing the small wing and the double-strut system, and relying only on the large wing supported by two slender non-pivoting struts.

Conclusions

The key design features employed on the *Decavitator* have resulted in a substantial maximum-speed increase over alternative human-powered vehicle concepts. In particular, the air propeller, pivoting large takeoff wing, solid-carbon-fiber hydrofoil construction, and low-drag pontoons combine to allow a very small underwater drag area and high propeller efficiency at top speed. Additional gains can be realized primarily with improved above-water streamlining.

References

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Decavitator Specifications

Vehicle weight	48 lb	22 kg	
Rider weight	140 lb	64 kg	design
	160 lb	73 kg	max
Rider position	semi-recumbent		
Overall length	20 ft	6.1 m	
Overall width	8 ft	2.4 m	
Air prop diameter	10 ft	3.0 m	
Drive	1/4" pitch stainless steel chain		
Gear ratio	2:1 prop to pedal speedup		
Large wing area, span	140 in^2 , 60 in	0.09 m^2 , 1520 mm	
Small wing area, span	52 in^2 , 30 in	0.034 m^2 , 760 mm	
Trim surface area, span	7.5 in^2 , 9 in	0.0048 m^2 , 230 mm	each (2 used)
Vertical strut area	10–30 in^2	0.006–0.02 m^2	(depending on operating mode)

Figure 1. *Decavitator* 3-view. Aerodynamic fairings not shown.

Figure 2. The *Decavitator* flying on the small wing in a practice run.

Figure 3. Transition sequence from two- to single-wing mode. Large wing pivots out of the water into streamlined receptacle.