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Multiphase Flow on a Ventilated Marine Propeller and Rudder

Abstract:

Multiphase flow around a fully ventilated, small, high speed marine propeller and a steering appendage is considered. Starting with a brief introduction to propellers designed for subcavitating, supercavitating, and ventilating operation, a physical description of the flow around a ventilated propeller entering the water is then given. The regimes at various advance coefficients can be categorized into three conditions: base ventilated, partially cavitating, and fully ventilated.

Using an example propeller, dimensional analysis is used to examine the descriptive dimensionless parameters: Froude number, Weber number, cavitation number, and Reynolds number. Near the blade, under normal operating regimes, the flow may be considered highly supercritical, independent of surface tension effects, cavitating, and inviscid, but with boundary layer effects.

The phenomenon of spray formation due to decreasing Weber number after blade impact on surface entry and water entrainment during blade exit is discussed. Fraction of total body volume sprayed can be as much as 12%.

A brief explanation of surface piercing appendage ventilation versus cavitation behavior is given. These characteristics dictate successful rudder geometry that may be counter-intuitive.

Due to the complex multiphase flow phenomena, the wedge cross section has evolved as the most successful cross section for surface piercing propellers and appendages.

An example of a ventilating propeller is presented, along with pictures of a complete hull operating at speed.

Introduction:

Conventional propellers for slow speed marine craft have traditionally been designed to operate fully submerged, and in a regime absent of cavitation. As speed or power increase, the tendency to cavitate increases. During the vapor cavity collapse, water inertia can be high enough for severe impact loadings on adjacent surfaces. If left unchecked, this can cause propeller erosion and failure [4].

With high speed marine craft, it is difficult to avoid cavitation [4][6]. With a propeller designed to intentionally induce cavitation, it is possible to extend the cavity far enough such that the collapse occurs after the trailing edge has passed safely out of the way. These are called Supercavitating propellers.

With very high speed marine craft, hydrodynamic drag reduction becomes paramount, and cavitation is too difficult to avoid, no matter what the blade design. It was discovered that a propeller run only partially submerged can still generate acceptable efficiency, plus enjoy reduced drag from positioning powertrain shafts and housings above the water [6]. Also, atmospheric pressure air entrained into the leading edge cavity effectively avoids collapse impact[5].

To help express the magnitudes of some of the physical phenomena throughout this paper, a representative surface piercing propeller installed on a racing model hydroplane is used for demonstration. The Calculation Table in the Appendix shows results for this and a second propeller for comparison.

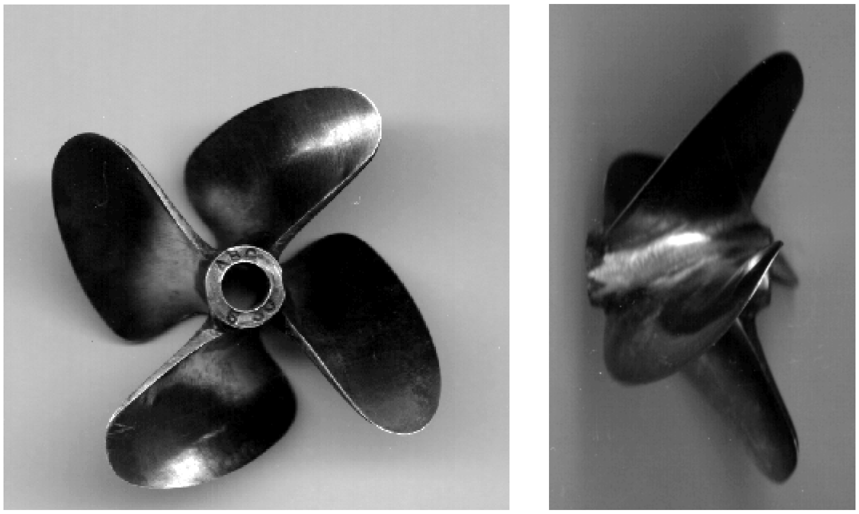

Fig. 1: The ABC S-30 4 blade.

Diameter	*60mm*
Pitch	*145mm*
Blades	*4*
Advance coefficient at top speed	*1.5*

Moderate trailing edge cup, blade area arranged for sprint course operation, operates at 30% submersion.

Installed on a *Roadrunner outrigger hydroplane*

Fig. 2: The Roadrunner outrigger hydroplane.

Top speed (sprint setup)	*33 m/s (73 MPH) (63 kts)*
Engine power	*3.3 kW (4.5 HP)*
Shaft speed (direct drive)	*22,000 rpm*
Boat mass	*3.6 kg (7lb, 13oz)*
Steady turning ability	*$37 m/s^2$ (3.8 g's)*

Discussion:

Dimensional Analysis:

Starting with the Navier-Stokes equations,

$$\rho \frac{\delta u_j}{\delta t} + \rho u_k \frac{\delta u_j}{\delta x_k} = -\frac{\delta p}{\delta x_j} + \mu \frac{\delta^2 u_j}{\delta x_i \delta x_i} + \rho f_j \qquad (1)$$

Dimensional analysis shows that several dimensionless parameters are useful for describing surface flows [10].

The Froude number describes the ratio of inertia to gravitational forces.

Propeller Froude number, $Fr = n\sqrt{\frac{D}{g}} = 29$ (2)

Where **n** = propeller rotational speed, **D** = propeller diameter, **g** = gravitational acceleration [7].

A Fr much larger than unity implies that inertia effects dominate gravity effects [1][8][10]. In this case, little hydrostatic pressure builds in only a few cm of water depth compared to several kilowatts of engine power delivered to the small area.

However, the hull still leaves a significant wake. The hull's sponsons barely touch the water (Fig. 3), and the rudder and turn fin impart minimal side loads during the straightaway, so the propeller must be responsible.

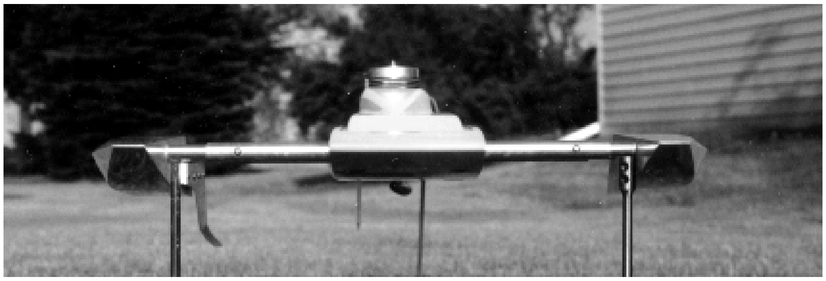

Fig. 3 Front view of hull showing small water surface contact area.

Far behind the hull, the thrusted water's inertia dissipates into the bulk flow, but the blade has carved a trough in the water surface. Now that the characteristic velocity has lowered, Fr approaches unity. At this point, the only significant forces on the water are hydrostatic pressure and gravity body force, and the trough's walls propagate along the surface as the narrow, straight wake. The waves are slow compared to the boat, yet they are still initiated by the propeller passage.

The Weber number describes the ratio of inertia forces to surface tension forces.

$$We = \frac{\rho V^2 L}{\sigma} = 650 \qquad (3)$$

Where ρ is the water density, **V** is the propeller tip velocity, **L** is the propeller leading edge radius, and σ is the surface tension of water at standard conditions [7].

A Weber number much larger than unity implies that inertia effects dominate the surface tension effects near the blade [10]. Far from the propeller, as we will see later, the water's kinetic energy dissipates in space, and surface tension breaks up the vertically jetted water into a coarse spray.

The Cavitation number describes the ratio of pressure forces to inertia forces.

For the example propeller, the Cavitation number on the leading face,

$$\sigma_c = \frac{\left(P_{atm} - P_{vapor}\right)}{\rho V^2} = 0.04 \qquad (4)$$

Where $\mathbf{P_{atm}}$ = atmospheric pressure, $\mathbf{P_{vapor}}$ = water vapor pressure at standard temperature, ρ = water density, **V** = propeller tip velocity.

A small σ_c implies that at these tip velocities and liquid inertias, atmospheric pressure is inadequate to prevent vapor cavity formation. A subcavitating propeller design operating at such a small σ_c would suffer from poor efficiency and severe cavitation damage.

Since the propeller is allowed to operate with only a portion of the blade submerged, atmospheric air is entrained into the cavity while the descending blade pierces the surface. The atmosphere maintains pressure in the cavity well above the water vapor pressure, which avoids cavity collapse entirely. This increased pressure on the forward face adds drag, but is offset by the reduced appendage drag from the strut, hub, driveshaft, and stuffing box, which can be enormous at high Reynolds numbers.

Notice that there is no adverse pressure gradient on the trailing face to allow cavity formation.

The Mach number for the example propeller is:

$$Ma = \tfrac{V}{c} = 0.2(air) = 0.05(water)$$

Where **V**= propeller tip velocity, **c** = speed of a sound wave in the liquid

This is considered well within the subsonic regime, and compressible effects can be ignored for most of the flow [8]. However, as we will see later, local stresses during surface piercing can cause compressibility effects.

Transition from Base Ventilation to Full Ventilation:

There are three flow regimes as the propeller blade enters the water, depending on the magnitude of the advance coefficient [5].

Advance coefficient, $J = \frac{V_e}{nD}$

Where $\mathbf{V_e}$ = boat speed, **n** = propeller rotational speed, **D** = propeller diameter

A high **J** implies low load, high speed operation, while a low **J** implies high load, or acceleration from low speed [7].

At high advance coefficients, the water stays attached to both the front and rear propeller faces [5] (Fig. 4). This is termed "Base Ventilation".

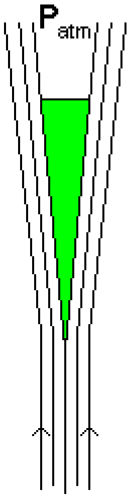

Fig. 4: Base ventilation at high advance coefficients.

If the foil gets thinner before the trailing edge, ventilation will begin at the maximum thickness position along the chord [5].

As advance coefficient lowers, a vapor cavity forms at the leading edge, less than one chord in length. This is termed "Partially cavitating". Propeller efficiency drops in this range, due to the unsteady action of cavity formation and collapse, and the increased cavity thickness.

At still lower advance coefficients, the leading edge cavity extends all the way back, and is vented to the atmosphere. This is termed, "Fully Ventilated" (Fig. 5).

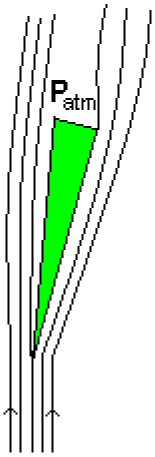

Fig. 5: Fully ventilated foil at low advance coefficient.

Flow behind a surface piercing appendage:

In an effort to reduce appendage drag, some racers have experimented with thinner rudder cross sections, but encountered the unexpected side effects of increased drag and high speed instability.

At low speed, there is only a small water depression behind the appendage. The trailing gravity wave is fast enough to keep up with the rudder.

With more speed, the depression gets deeper, and longer. At a certain speed, the cavity extends to the bottom of the rudder (Fig. 6). As Fr exceeds unity, the gravity wave can no longer stay attached to the rudder trailing edge.

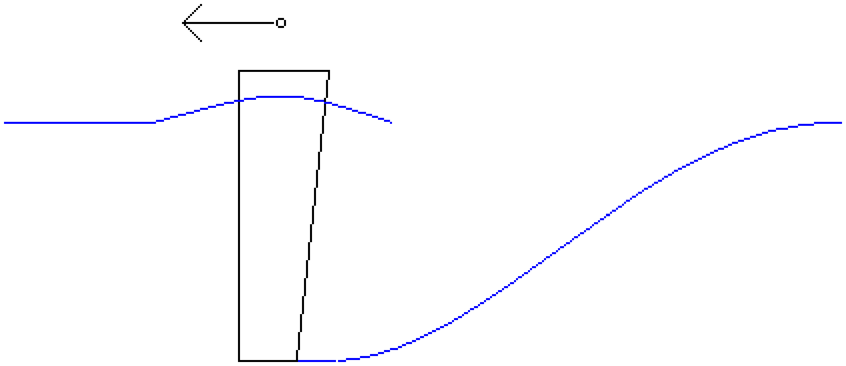

Fig. 6: Detached gravity wave at Fr>1.

With still more speed, the cavity grows longer at the bottom, but the top begins to narrow and close, reaching forward to the rudder. When this happens, the cavity is sealed from atmospheric pressure, and the sudden switch to cavitating flow instead of ventilating flow causes a large, sudden jump in drag (Fig. 7).

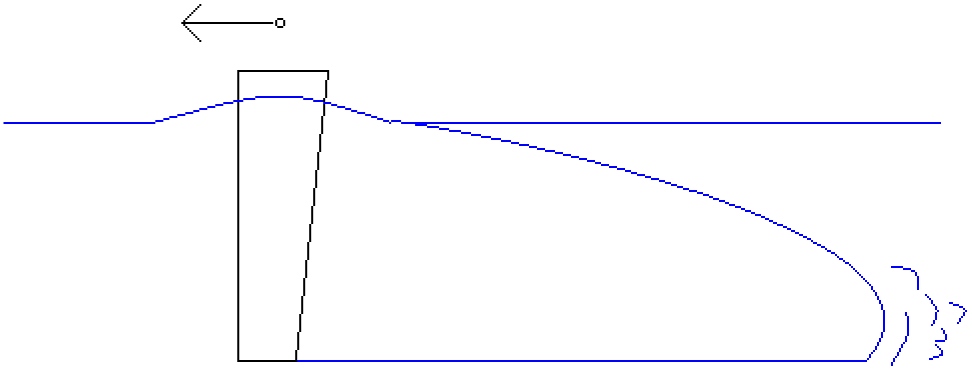

Fig. 7: Cavitating flow after closure to atmospheric filling.

The extra drag slows the boat, but more importantly torques the hull into an undesirable yaw attitude (rudder is typically offset from the hull center of mass to avoid blocking the propwash (Fig. 8)).

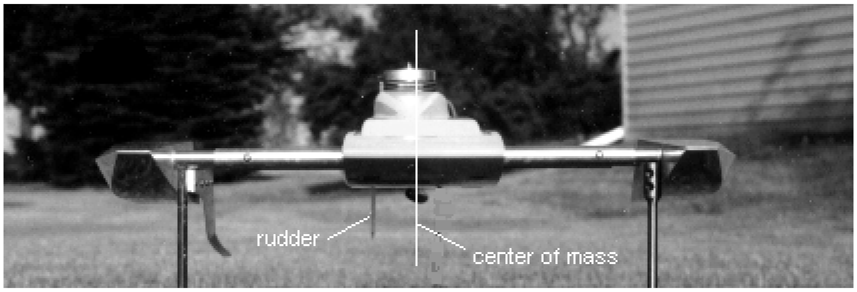

Fig. 8: Offset rudder.

As the boat slows, it breaks free of this condition, and speeds up again. This causes a cycle of unstable drag and yawing forces on the hull, which completely upsets the vehicle dynamics.

At high speeds, the cavity requires large amounts of air to fill the void. Also with high speed, the air pressure lowers, which tends to press the walls of water together at the water surface. The narrower cavity opening further aggravates the filling capacity, and rapid closure ensues [11].

Unlike the propeller, the rudder is not generating significant thrusting forces during a large portion of its operation. Any time the hull is not turning, the rudder will stay in the base ventilation regime, which generates a narrow cavity for a given foil thickness, which is desirable for drag reduction. However, this same narrow cavity can cause the unwanted cavity closure phenomenon. Successful rudders are often thicker than intuition would predict.

Water entrainment and spray formation

Surface drive hulls are notorious for the water they spray into the air (Fig. 9).

Fig. 9: High volume of sprayed water.

There are three modes of water entrainment into the air:

* Trailing face pressure forces push some of the surface water upward (Fig. 10).

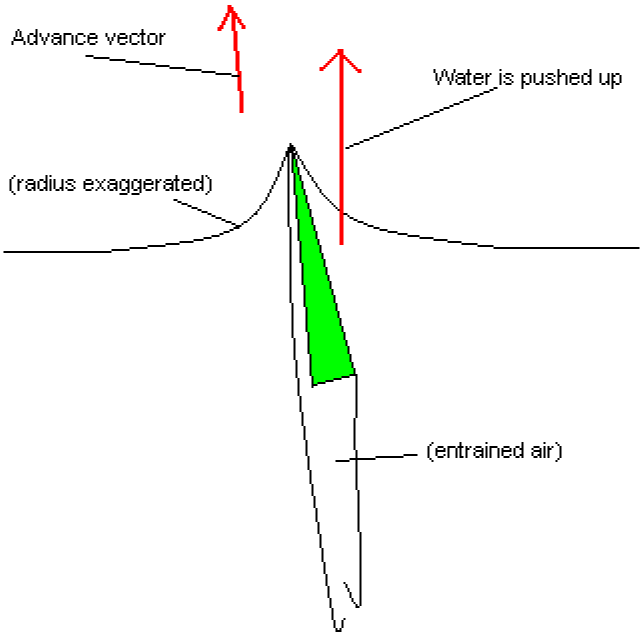

Fig. 10: Trailing propeller face pushing surface water upwards. Notice the advance vector is declined versus blade orientation.

* Viscous shear forces from the blade pressure face pull surface water upward, then spill it radially off the wetted blade side and trailing edge (Fig. 11).

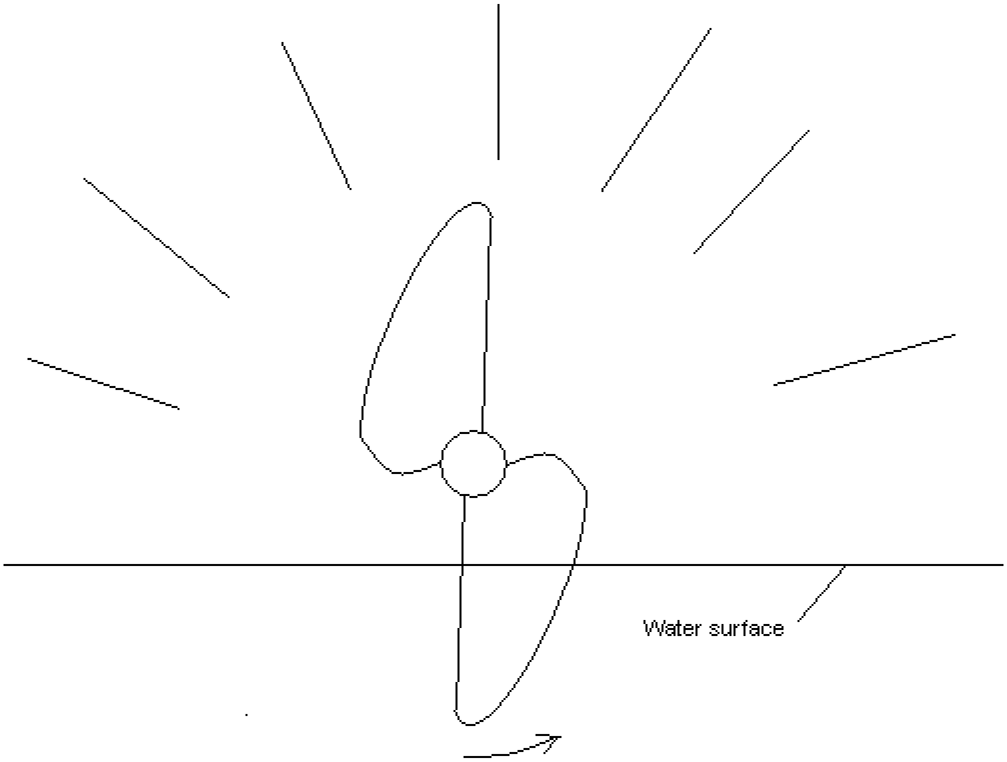

Fig. 11: Propeller throwing entrained water radially.

The stream Reynolds number in the water at operating speed is on the order of 4,000,000. At this Re, boundary layer theory predicts a low local Re near the blade on the pressure side and the cavity on the suction side, and the formation of viscous region [10]. As the upswinging blade exits the surface, these viscous forces keep some of the water with the blade. Blade exit can entrain 7 to 12% of the body volume of water into the atmosphere [5].

* Leading edge blade impact during blade entry splashes the surface water upward (Fig. 12).

While the Mach number is only about 0.2, the small cross-section leading edge impacting the water surface at high speed significantly stresses the water, causing compressible effects [9]. This impact energy is distributed to the water as potential energy as it increases height [9], and kinetic energy as it streams away from the impact site.

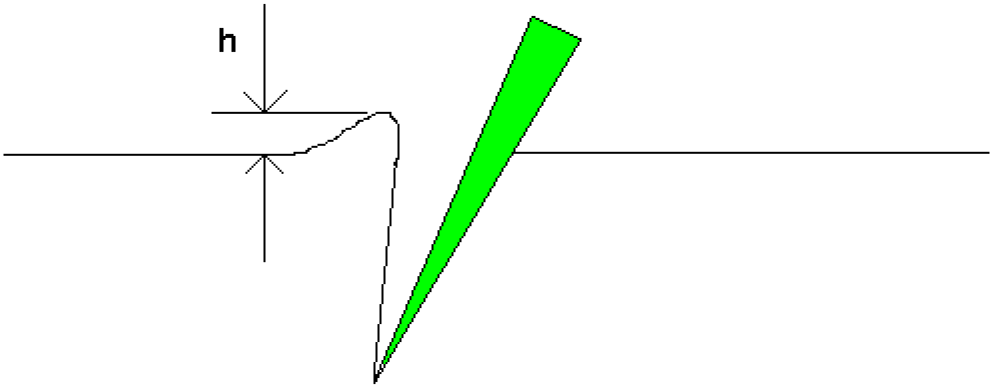

Fig. 12: Splashed water after blade impact. Notice that breakup into spray occurs far from blade.

As the spilled or splashed water expands radially from the blade, it slows and thins. With lower inertia and lower local radii, surface tension breaks it up into the familiar coarse spray. Though the Weber number close to the propeller is too high for surface tension to be important, a spray still forms.

Since the spray itself has significant inertia [5], any upward component represents wasted energy. Also, impact energy required to pierce the surface directly resists engine torque.

Spray formation is used as a tuning tool for performance. A high spray indicates losses that need to be addressed. A low-slung, rearward facing spray indicates better control over the inefficiencies.

Ways to reduce spray losses:

Development on high speed hydroplanes has resulted in some methods for reducing spray losses.

Increase edge cup.

Most of the entrained water is spilled off the propeller edges [3]. Cupping the edges can redirect the spillage rearward, regaining thrust (Fig. 13).

However, it is important to note that this modification will reduce the propeller lifting forces. This can cause the rear of the hull to lower, which increases the overall angle of attack. A high angle of attack can trap excess air, and lift the entire hull off the water [2].

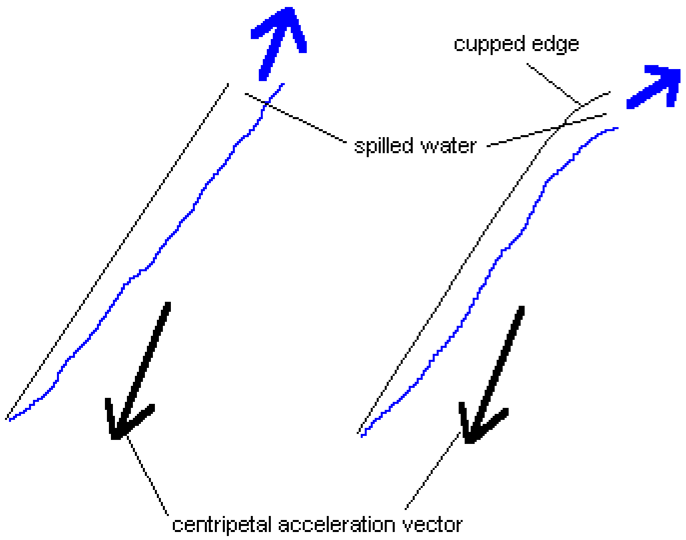

Fig. 13: Edge cup can redirect radial spillage rearward, but will affect lift.

Maintain a sharp leading edge.

A sharp leading edge helps reduce impact forces on blade entry [9], and also helps maintain a small cavity thickness. With less impact, less energy is wasted splashing the water upward. A thinner cavity reduces pressure drag, and reduces the surface area available for viscous forces to entrain water into the air during surface exit. Years of experience with race boats has shown that maintaining a sharp leading edge is one of the most important ways to improve surface piercing propeller efficiency.

Conclusion:

To the novice racer with some knowledge of fluid mechanics, the wedge profile appears to be far from optimal. Many times, thinkers will try a conventional airfoil profile, only to notice high instability, vastly increased drag, and lower thrust (or turning) forces. Unfortunately, the flow phenomena around a fully ventilated propeller are very different from the inviscid, incompressible, single phase fluid assumptions which the NACA used for developing their well known blade sections.

The wedge profile allows the propeller and appendages to take advantage of the air's low viscosity and density to reduce drag, while taking advantage of the water's high density to generate thrust or lateral forces for pushing the hull. Also, it takes advantage of atmospheric pressure to avoid cavitation bubble collapse damage, vibration, and noise.

Future Study:

Attention to propeller blade planform design and blade count has recently shown significant progress towards higher performance. Unfortunately, the multiphase flow aspects of ventilating operation force the subject to remain complex and highly empirical, which calls for thorough study.

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