Alternatives for Enhancement of Transport Economy in Underwater Gliders

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An analytical flight survey was conducted of the net transport economy of the present generation of underwater gliders, referred to as legacy gliders, [1]-[3]. Net transport economy (*NTE*) is the total energy consumed (including hotel loads) per Newton of net buoyancy (*B*) per meter traveled, and is a commonly used energetics metric in transportation sciences for representing the cost of transport. The analysis determined that legacy gliders operate in a scale regime equivalent to that of bats and small birds (Fig. 1).

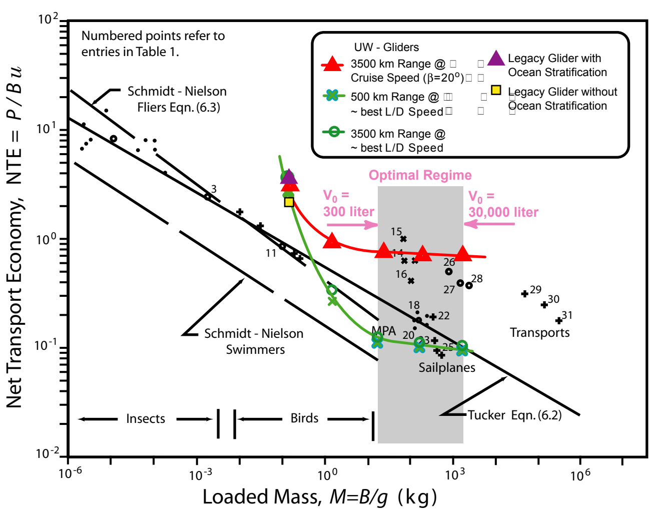

Figure 1. Net Transport Economy (NTE) for natural and man-made flyers, from [4], verses underwater gliders. Legacy gliders are shown as magenta triangles and yellow squares. The flying wing underwater glider concept is evaluated at cruise speed (red) and near best L/D speed (green).

Gliding performance of the legacy glider does not match the transport economy of its bird and bat counterparts because of the way it is flown, insufficient loading of the wing, excessive wetted surface area, and inefficiencies of the buoyancy engine. Legacy gliders are not flown in the most transport efficient manner. They are flown at steep glide angles in order to profile ocean water masses. If they were flown at the flattest glide slopes within present capability (L/D_{max}), their transport economy would improve three fold. To do so would require the controller to trim the glider for nose high attitudes during descending glides and nose low attitudes during ascending glides. Present control systems lack sophistication and supporting flight instrumentation necessary for maintaining stable high angle of attack flight attitudes.

The present glider shapes are analogous to gliding blimps, and have excessive wetted surface area for the wing loading at which the gliders are flying. Two remedial approaches were studied: increasing the wing loading by increasing the capacity of the buoyancy engine and reducing the wetted surface area. Numerous sets of computations based on higher ratios of net buoyancy volume to total vehicle volume found that it is possible to make underwater gliders perform very close to the transport economy of natural flyers when operating in the present scale regime of birds. In larger scale regimes, these computations found that underwater gliders can equal or better the transport economy of some of the most efficient man-made flyers. Numerical modeling was also performed to seek more efficient shapes having less wetted area (A_t) per unit area of wing (A), such as flying wings and blended wing-body configurations, wherein nearly all of the wetted area is efficient lift generating area (Fig. 2).

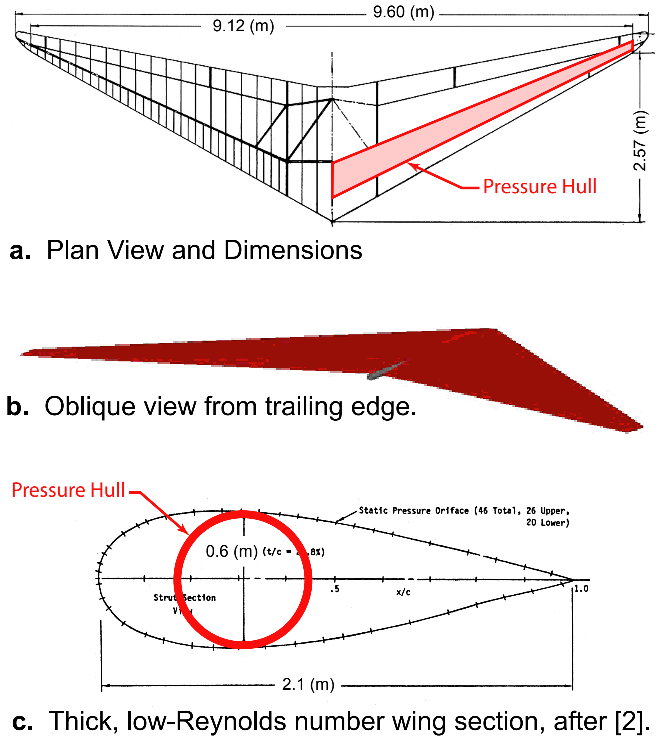

Figure 2. Flying wing underwater glider concept to minimize relative wetted area (A_t / A).

Flying wing shapes were found to have superior range and speed capability for less energy consumption than more conventional bodies of revolution fitted with wings (Fig. 1 and 3). The green curve in Fig. 1 shows that large flying wings can achieve 2 orders of magnitude improvement in net transport economy over present capabilities of legacy gliders. The flying wing glide polar in Figure 3 shows a 7-fold increase in glide range for any given dive cycle. Maximum speeds as high as 4.5 (m/sec) (9 knots) are also possible. The remaining alternative for reducing the wetted surface area would be to reduce the volume requirements of the glider body by placing the batteries outside the pressure hull in free flooding compartments within the hydrodynamic hull. This concept was not pursued due to uncertainties in the status of pressure compensated battery technology.

The buoyancy engines that propel the legacy gliders do not recover the energy on descent that was expended on ascent in order to overcome ocean stratification and hull compressibility. Figure 4 gives computations of the ratio of the total pump energy expenditure to the flight energy during a 1000 (m) gliding dive cycle. Note that a hull slightly more compressible than sea water gives the minimum pump energy expenditure, as it somewhat compensates for the higher density below the thermocline (this advantage is slight). For legacy glider hull compressibility of k=3e-6, we pay ~6% higher energy cost over a hull with k=4.4e-6. The energy cost due to the density gradient varies from ~8 % of the flight energy (at k=4.4e-6) in high latitude environments to as much as 23% in equatorial environments. This result is tempered

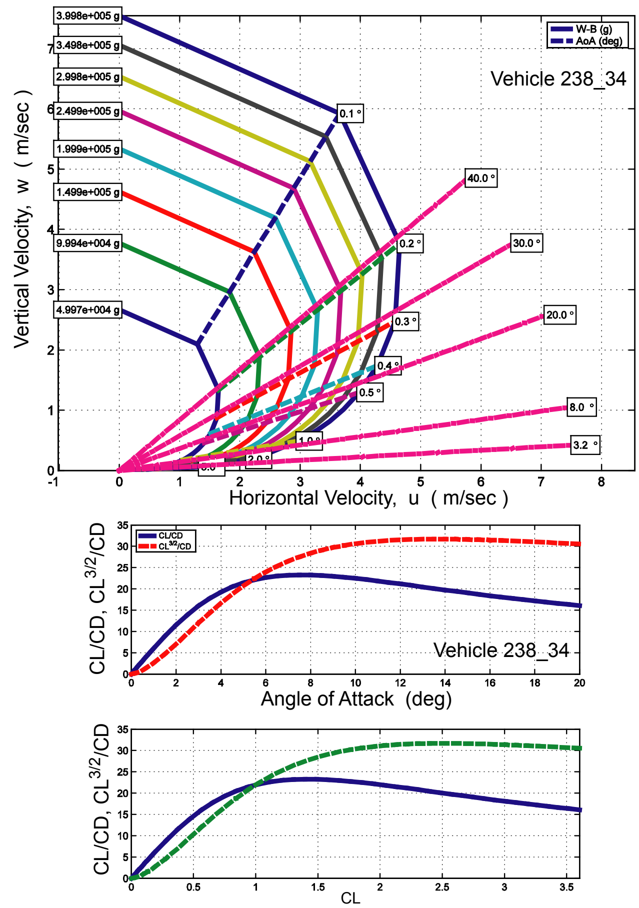

Figure 3. Glide Polar (upper), lift drag and endurance ratio verses angle of attack (middle) and verses lift coefficient (bottom) for single payload flying wings. Root Cord = 2.10 (m), Root Section Thickness = 0.61 (m), Span = 9.60 (m), Wing Area = 11.52 (m^2), and Volume = 1,566 (liters).

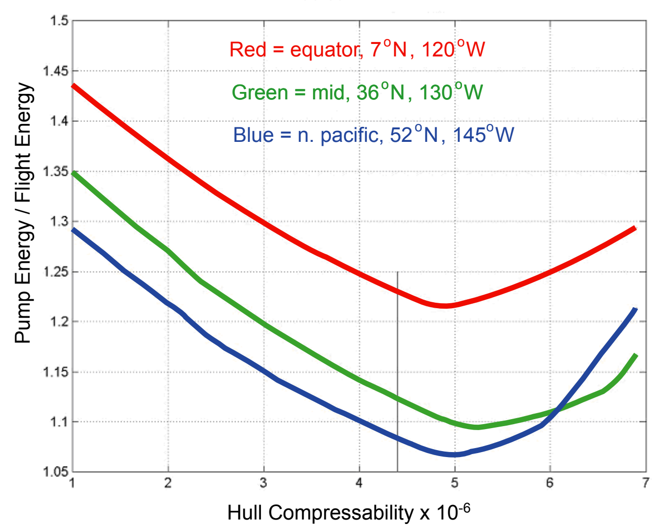

Figure 4. Ratio of buoyancy pump energy consumption to flight (thrust) energy as a function of hull compressibility (k) during round trip gliding dives to 1000m depth in three ocean environments : equator (red) mid-latitudes (green) high northern latitudes (blue) [2].

by the fact that the seasonal thermocline is shallow in relation to the total diving depth, but the penalty in not recovering the *pressure/volume* work during descending glides in more strongly stratified coastal environments (as found near major rivers) may be considerably higher. From the combined effects of hull compressibility and density stratification, the buoyancy engine is typically consuming about 30% more than the flight energy required. Flying the UW glider to deeper depths is intrinsically more efficient. Energy consumption increases 30% when the depth excursion of the glide profile is reduced from 1000 (m) to 100 (m). This is due to 2 factors: 1) the glider must penetrate the thermocline a greater number of times over any given gliding distance when the depth excursion is reduced, and 2) the buoyancy engine pump is less efficient at lower pressures (shallower depths). A minimum ratio of net buoyancy volume to total vehicle volume was found ($n_b = V_{buoyancy} / V_0 \sim 0.4\%$), beyond which, bigger gliders always achieve better transport economy. This improvement is accompanied by higher speed capability (Fig. 5).

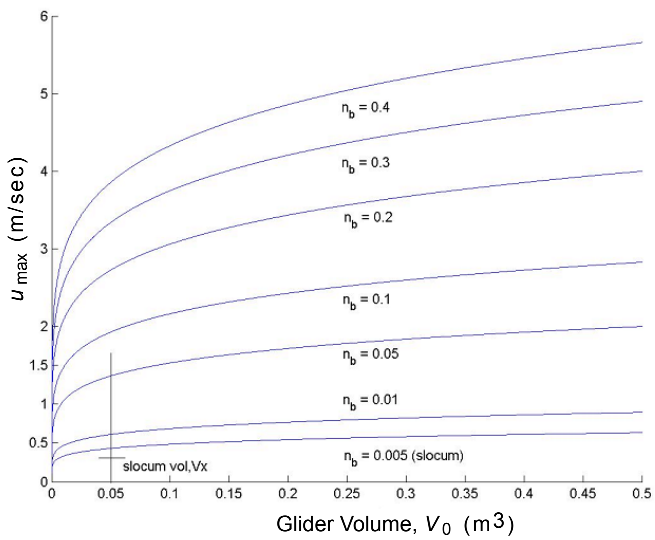

Figure 5. Maximum cross country speed u_{max}, as a function of total vehicle volume, V_0, for various lung capacity factors, n_b; where, $n_b = V_{buoyancy} / V_0$. [6]

Maximum along coarse speed in still water is always obtained at a 35 degree glide angle, regardless of vehicle shape or other hydrodynamic properties. Winged bodies of revolution with maximum buoyancy engine capacity (n_b) are the optimal combination for maximum speed (Fig. 6). For a given n_b, flying wings of equivalent vehicle volume are slower then winged bodies of revolution, but have superior range and transport economy and require fewer dive cycles (and less near surface exposure time) for a given distance traveled.

Acknowledgments

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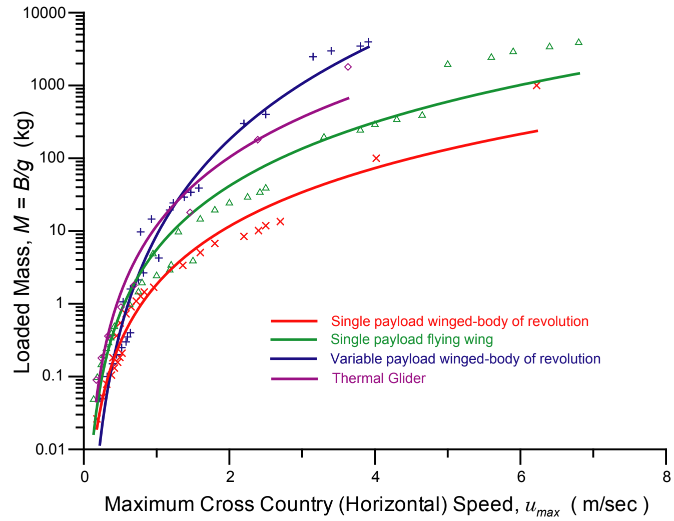

Figure 6. Maximum cross country (horizontal) speed for an underwater glider due to variation in the loaded mass (M = B / g) for winged-body of revolution carrying single (small) payloads (red); winged-body of revolution carrying bundled (large) payloads (blue); and the flying wing carrying single (small) payloads (green); thermal glider in winged-body-of-revolution configuration with single payload (purple).

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