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Morphing hull concept for underwater vehicles

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ABSTRACT

Morphing or adaptive structures may be of interest in underwater vehicle design due to their potential for optimizing the operational envelopes of complex vehicles. Adaptive structures have been researched heavily and put to use extensively in the aerospace industry. This paper examines a possible use and benefit associated with morphing structures with unmanned underwater vehicles (UUVs). The growing résumé of applications associated with UUVs as well as their unique abilities make them an excellent subject of study for morphing concepts. This paper focuses on possible uses of flexible hull morphing, specifically the benefits associated with such adaptability in terms of range, endurance, and speed. This research proposes a UUV system which has a flexible hull wrapped around a standard pressure hull. The annulus created between the pressure hull and the flexible hull is used for the storage of expendable energetics, in this case diesel fuel. Storing fuel in the newly created annulus also eliminates the need to waste space within the pressure hull storing fuel and thus the pressure hull may also be shrunk. This paper focuses on the benefits of morphing where the shape of the flexible hull remains the same but the diameter of the outer hull is shrunk in concert with the consumption of fuel thus decreasing the drag profile of the vehicle, resulting in increased vehicle range. Two different UUV missions were outlined: (1) constant speed survey and (2) slow speed survey with high speed excursion. For the slow speed survey mission, semi-submersible heavy vehicles carrying in the range of 50,000 kg of fuel could realize increases of range close to 40% when compared to a similarly sized vehicle without the adaptive capabilities. Small vehicles on the other hand, show limited benefits of diameter morphing, gaining less than 5% in range over the non-adaptive system. Excursion missions during which a surveying operation must be augmented with some sort of high speed maneuver show more significant benefits with a morphing system. The results show that diameter morphing is not viable in all situations, yet the concept shows promise for certain long range/long endurance UUV missions, as well as missions that require occasional high speed operation.

1. Introduction

The description of the desirability of four classes of unmanned underwater vehicles (UUVs), tailored for specific missions, in the The Navy Unmanned Undersea Vehicle (UUV) Master Plan (2004) is indicative of interest in larger displacement vehicles. Simultaneously, the consideration of hybrid powerplant concepts for unmanned underwater vehicle (UUV) design has enjoyed some interest (Miller et al., 2008; Peters, 2007; Dame et al., 2006; Griffiths et al., 2005; Cai et al., 2007). Generally, hybrid design concepts have been viewed in the context of a single vehicle containing two (or more) different power systems. The individual power system is tailored for a particular operating regime such as low power/long endurance, high power/high speed, and others. The power systems might be made up of different energy conversion devices, such as fuel cells or turbines; or fuel/oxidizer combinations. The objective of the current work is different, however. Here we propose to study the feasibility of a UUV design that is made hybrid by its ability to geometrically morph or change shape to enhance mission endurance and effectiveness.

For an example of the use of a large displacement UUV, consider an operational scenario consisting of a high speed transit to an operations area, followed by a long duration and low-speed

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Nomenclature

a, b, c, t	fin parameters (Fig. 7)
C_{fins}	fin drag coefficient
C_{FO}	ratio of oxygen storage to fuel storage system volumes
CD_A	component of UUV combined form and skin friction drag coefficient
CD_{SR}	surface roughness enhancement of drag coefficient
d	diameter of constant UUV cross-section
D	drag
L	total vehicle length to truncated tail cone tip
L^*	total vehicle length to virtual tail cone tip
L_c	length of constant cross-section portion of UUV
L_t^*	length of aft tapered portion of UUV
P	power
Re_L	Reynolds number based on UUV velocity and total length
S	surface area
U	velocity of UUV
ΔCD_{AF}	addition to drag coefficient due to aft fins
ρ_{Seawater}	density of seawater
$\rho_{\text{Vehicle\_Finish}}$	density of vehicle at end of mission
$\rho_{\text{Vehicle\_Start}}$	density of vehicle at start of mission

survey, and ending with a high speed transit back to a tender ship or embarkation point. A simple long range, low speed operation might be facilitated as well. Range may be increased by employment of diameter reduction or telescopic length reduction morphing, which has as its effect the reduction of profile and skin friction drag. This type of morphing has been touched upon by Nadolink (1993) who describes the idea of an external "inflatable" hull attached to an interior rigid hull. Additionally, one can envision an initially heavy morphing UUV using a lifting-body morph for a high-speed transit to maintain depth control. During the survey phase, with the UUV near neutral buoyancy, the vehicle may employ a variable diameter morph. At the end of the survey the vehicle is light, thus requiring a negative-lifting body morph for the high-speed final stage. The idea of a lift producing morph is specifically not a topic of this paper and would require additional analyses of the effect of drag induced by the lifting action. A very preliminary shape is described by Rufino (2008).

2. Method and rationale

2.1. Expendable energetics

Our investigation centered on the use of geometric morphing to reduce the vehicle diameter and lengths, as reactants are expended and exhausted out of the vehicle, thus reducing drag and power requirements as the vehicle mission proceeds. The usefulness of this concept is predicated on the desire to make use of easily stored logistics hydrocarbon fuels like marine diesel or JP-5 (Kiely and Moore, 2002; Ghezel-Ayagh et al., 2007), and the recognition that these types of fuels can be used for both heat engine-based power plants or for solid-oxide fuel cells. Fig. 1 illustrates the basic idea. Although the sketch depicts a notional system employing oxygen, JP-5 fuel, and a solid oxide fuel cell; a large selection of oxidizers and energy converters are applicable. The "rigid" part of the UUV that contains the power plant, sonar, and other "dry" components is constrained by the inner cylindrical pressure hull. We assume here that the oxidizer storage medium whether compressed air, compressed oxygen, LOX (Haberbusch et al., 2002) or chemically-stored oxygen (Peters et al., 1994) must also be viewed as requiring an inflexible storage volume. Oxidizer of the type described typically requires pressure or cryogenic vessels for storage, hence the rigid requirement. If a liquid oxidizer like a hydrogen peroxide solution was employed, however, then the oxidizer as well as the more easily-stored logistics fuel can be contained in the outer, morphable, annular volume.

With hydrocarbon-fuel based energy systems, oxidizer volumetric storage requirements are typically much greater than liquid hydrocarbon storage requirements. Preliminary calculations indicate that the primary limit on the usefulness of this concept is described by the ratio of oxidizer system volume to fuel system volume. Fig. 2 represents volume requirements for a number of notional UUV powering concepts. The parameter C_{FO} is defined as the ratio of the volume of the oxygen storage apparatus, not just the oxygen storage material, to the volume of hydrocarbon fuel storage apparatus. It ranges from a high of ~6 for conventional high pressure gaseous oxygen, GOX, to a low of ~2–2.5 for more advanced cryogenic oxygen, LOX, (Haberbusch et al., 2002) and chemical, ChemOx (Peters et al., 1994), storage methods. A value for C_{FO} of 6 corresponding to conventional high pressure (~340 atm) oxygen is considered a baseline value here. Note that the choice of a solid oxide fuel cell (SOFC) or Stirling heat engine does not strongly affect the results.

Fig. 3 illustrates the effect of oxidizer storage on vehicle range. The calculations used to generate this figure assume a 1.22 m diameter and 6.1 m long vehicle, with an assumed hotel power load of 1 kW. The behavior of the range versus speed curves shows an obvious optimum speed which always results when a hotel load is assumed. Below the optimum speed, too much energy is used by the hotel load; while above the optimum, too much energy is used pushing the vehicle through the water. The maximum range and optimum speed will vary as a function of the size of the vehicle and the size of the hotel load. More to the point, this figure illustrates that for reasonable (~340 atm and $C_{FO}=6$) compressed gas storage very little advantage is accrued relative to the baseline non-morphing vehicle. If different concepts, like those which employ LOX or chemical oxygen storage, are considered with $C_{FO}<2.5$, the benefits may be substantial.

Note that if a liquid monopropellant like Otto II fuel or a combination of liquid oxidizer like a hydrogen peroxide solution and logistics hydrocarbon fuel is employed, with $C_{FO}=0$, the range improvement should be even greater. Similarly the use of a semi-submersible air-breathing diesel powered system like the Lockheed Remote Minehunting Vehicle (Larkin and Thomsen, 2003) or the International Submarine Engineering Ltd. Dorado vehicle (Nguyen and Hopkin, 2005; Watt, 2002; Jane's Underwater Warfare Systems, 2010; Ferguson, 2003) suggests similar benefits. With any of these systems, all of the initially stored and expendable material is expelled from the vehicle and the final diameter is dictated by the minimum permissible diameter required for storage of energy conversion devices, sonar arrays, or other fixed size constraints.

2.2. Neutral buoyancy

An issue common to the vehicles of interest here, as well as to underwater vehicles in general, is the requirement of maintaining attitude. In general, neutral buoyancy is most desirable for a UUV. This is particularly challenging if reactant products are exhausted overboard, or even if products are simply moved to different