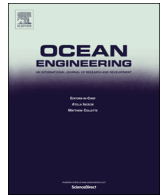




Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Understanding the power requirements of autonomous underwater systems, Part I: An analytical model for optimum swimming speeds and cost of transport

A.B. Phillips^a, M. Haroutunian^{b,*}, A.J. Murphy^b, S.W. Boyd^a, J.I.R. Blake^a, G. Griffiths^c

^a University of Southampton, Southampton, SO17 1BJ, UK

^b Newcastle University, Newcastle, NE1 7RU, UK

^c National Oceanography Centre, University of Southampton Waterfront Campus, Southampton SO14 3ZH, UK

ARTICLE INFO

Article history:

Received 16 April 2015

Accepted 7 December 2015

Keywords:

Bioinspiration

Autonomous underwater vehicles

Hydrodynamics

Cost of transport

ABSTRACT

Many marine species exhibit capabilities that would be desirable for manmade systems operating in the maritime environment. However, without detracting from the potential, if bioinspiration is to prove beneficial, it is important to have a consistent set of metrics that allow fair comparison, without bias, when comparing the performance of engineered and biological systems. In this study we focus on deriving an unbiased metric of performance applicable to marine animals and engineered subsea vehicles for one of the most fundamental of properties; that of the energy cost of locomotion. We present a rational analytical model of the physics behind the total energy cost of locomotion applicable to both biological and engineered autonomous underwater marine systems. This model proposes the use of an equivalent spheroid efficiency as a fair metric to compare engineered and biological systems. The model is then utilised to identify how changes in mass, speed, spheroid efficiency and hotel load impact the performance of the system.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Biologically inspired swimmers are flourishing with various prototypes of a new generation of biomimicked vehicles being built. These include the “GhostSwimmer” which is being tested by the US Navy (Telegraph, 2014), the “Mantabot” which mimicks the swimming of a ray (Unmanned, 2012) and the Aqua Jelly (jellyfish) developed by Festo (Festo, 2013). Bioinspiration and biomimetics have great potential to lead to new concepts in the design and implementation of engineered artefacts swimming within the oceans (Bandyopadhyay, 2005). Therefore, it is technically relevant to investigate the possible advantages of the systematic design and build of bioinspired vehicles.

The routine activities or missions of both pelagic marine animals and free swimming autonomous underwater vehicles (AUVs) require these systems to transit between multiple locations. For both biological and engineered systems there is an evolutionary or design driver towards reducing the total energy consumption of the system when completing these journeys.

AUVs are almost invariably deployed with a finite energy store; by reducing the energy cost per unit distance travelled the range of the vehicle may be enhanced (e.g. Furlong et al. (2007) and Phillips et al. (2012)). For pelagic species swimming is the only alternative for most animals to find food, escape predators and reproduce successfully (Videler, 1993). Averaged over a period, the amount of energy acquired by an individual through feeding must exceed the amount of energy expended by daily activities, growth and reproduction. Based on optimal foraging theory, natural selection should operate to maximise the ratio of energy income to energy expenditure (Townsend and Winfield, 1985). Hence, the solutions adopted by marine animals to reduce their energetic requirements may provide inspiration to enhance the design of the next generation of free swimming AUVs.

Without detracting from the potential, if bioinspiration is to prove beneficial, it is important to have a consistent set of metrics that allow fair comparison, without bias, when comparing the performance of engineered and biological systems. However, such an unbiased comparator can be elusive given the disparity in the forms of biological and engineered components, even for those that essentially perform the same functions.

For example propulsive efficiency is often quoted by both engineers and biologists as a measure of the ratio of the effective

* Corresponding author. Tel.: +0191 208 6104.

E-mail address: maryam.haroutunian@ncl.ac.uk (M. Haroutunian).

Nomenclature

$(1+k)$	Form factor (-)	n	Number of samples (-)
$(1-t)$	Thrust Deduction (-)	P_H	In Water Maintenance power requirement (W)
a	Mass allometric scaling constant for in-water maintenance power (variable)	P_p	Propulsion power requirement (W)
A	Wetted surface area (m ²)	q	Proportion of system mass devoted to energy storage (-)
A_s	Wetted Surface Area of equivalent ellipsoid (m ²)	R	Range (m)
b	Mass allometric scaling exponent for in-water maintenance power (-)	Re	Reynolds number (-)
C_D	Drag coefficient (-)	R_{max}	Maximum range (m)
C_f	Skin friction coefficient (-)	t	Thrust deduction (-)
C_v	Viscous drag coefficient (-)	U	Forward speed (m/s)
COT	Cost of transport (J/kg/m)	U_{opt}	Optimum speed (m/s)
COT_{net}	Net cost of transport (J/kg/m)	α	Re scaling constant for skin friction coefficient (-)
COT_{opt}	Optimum Cost of Transport (J/kg/m)	β	Re scaling exponent for skin friction coefficient (-)
D	Diameter (m)	ϵ	Spheroid eccentricity (-)
D_s	Equivalent spheroid Diameter (m)	ϕ	Proportion of the system mass devoted to energy storage (-)
E	Gravimetric Specific Energy of Power Source (J/kg)	ζ	Equivalent spheroid efficiency (-)
L	Length (m)	ν	Kinematic viscosity (m ² /s)
L/D_s	Slenderness ratio (-)	ρ	Water density (kg/m ³)
m	Mass (kg)	τ	Scale factor (-)
		η_a	Actuator efficiency (-)
		η_p	Propulsive efficiency (-)

power to the power delivered to the propulsion system

$$\eta_p = \frac{\text{Effective Power}}{\text{Delivered Power}} \quad (1)$$

Numerous authors have quoted high propulsive efficiencies, η_p , for marine animals operating at turbulent Reynolds numbers using carangiform and thunniform type propulsion (high speed long-distance swimmers where virtually all movement is in the caudal fin). For example, the propulsive efficiencies of pseudo killer whales at 0.9 (Fish, 1996), bottlenose dolphins at 0.81 (Fish, 1993) and fin whale at 0.85 (Bose and Lien, 1989) are high compared with those of a typical propeller (Wageningen B5-75) open water efficiency of 0.5 to 0.7 (Carlton, 2007).

However, these results must be treated with caution. The action of any propulsor, be it an oscillating foil, propeller or water jet, will locally modify the flow around the individual. In turn modifying the resistance of a self-propelled individual compared to a towed (or passive) individual. There is inconsistency between the standard methods for accounting for this change in resistance (typically an increase) between biological and engineered systems.

For ships the increase in self-propelled resistance is included as part of the propulsive efficiency rather than as an increment on the drag. Thus the propulsive efficiency of an AUV is:

$$\eta_{p(\text{engineering})} = \frac{\text{Towed Resistance} \times \text{Velocity}}{\text{Propulsive Power to Shaft}} \quad (2)$$

While not universally accepted, in biology the influence of the propulsor on the 'drag' is often considered as an added resistance factor, λ , which is the ratio of the swimming thrust to passive drag:

$$\lambda = \frac{\text{Swimming Thrust}}{\text{Passive Drag}} \quad (3)$$

The added resistance factor is highly dependent on propulsive mode and accounts for drag increases due to large-amplitude lateral body movements that modify the water flow in the boundary layer and around the body, resulting in increased frictional and form drag (Webb, 1975). Experimental data collected by Webb (1975) shows that the drag coefficient for fish swimming at high Reynolds numbers can be up to four times that of a rigidly gliding fish. Importantly this added resistance is typically not included in the propulsive efficiency. Hence the propulsive

efficiency of a marine animal is often taken to be:

$$\eta_{p(\text{biology})} = \frac{\text{Swimming Thrust} \times \text{Velocity}}{\text{Power in wake}} \quad (4)$$

There are sound reasons for the differing approaches due to the measurement techniques available for engineered and biological systems (Webb, 1975). However, the consequence is that direct comparison of quoted propulsive efficiencies between engineered and biological systems is biased towards biological systems since biological values do not incorporate the added resistance due to the movement of the body. To enable a fair comparison:

$$\eta_{p(\text{engineering})} = \frac{\eta_{p(\text{biology})}}{\lambda} \quad (5)$$

In this work a combination of reduced-complexity analytical formulations and dimensional analysis is used to generate a comprehensive idealised analytical model of the cost of transport and optimum swimming speed of an individual, be it a biological or engineered system based on system metrics including equivalent spheroid efficiency. The analytical model provides enhanced understanding of the implications of propulsion and non-propulsion power requirements on the energetic performance of individuals. In Part II of this paper this understanding is used to explain trends in collated published swimming performance data, where a number of recent biological studies on individual species (Behrens et al., 2006; Clark and Seymour, 2006; Fitzgibbon et al., 2007; Korsmeyer et al., 2002; Ohlberger et al., 2006; Otani et al., 2001; Palstra et al., 2008; Rosen and Trites, 2002; Steinhausen et al., 2005; Tanaka et al., 2001; Tudorache et al., 2011; Williams and Noren, 2009) have allowed the creation of a significantly larger data sets than considered by previous comparative studies, e.g. Videler (1993) and Videler and Nolet (1990).

2. Analytical model

Due to the limited availability of energetic data for marine animals, empirical models have been previously proposed to supplement and enhance our understanding. Previous studies have developed equations for the optimum cost of transport and/or optimum swimming speed of marine animals using regression

Download English Version:

<https://daneshyari.com/en/article/5474340>

Download Persian Version:

<https://daneshyari.com/article/5474340>

[Daneshyari.com](https://daneshyari.com)