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A bio-inspired climb and glide energy utilization strategy for undersea vehicle transit

Timothy F. Miller

TFM-Technical, LLC, State College, PA 16803, United States

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ABSTRACT

Marine animals have been the bio-inspirational source for some novel concepts for locomotion, sensing, and the intelligent control of undersea vehicles. There has been little (if any) research in the area of bio-inspired energy utilization strategies applied to undersea vehicles. For example, there are reasons why some fish swim at a specific cruise speed; why some fish move by burst acceleration to higher speeds followed by coasting; and why some negatively buoyant fish alternately glide downwards, and then swim upward. The goal of this study is to develop the theory and models of the climb and glide form of autonomous undersea vehicle transit in a form that can permit assessment of future practical technology insertions (such as drag reduction and wing design). In addition, existing theory was expanded to address vehicles with significant wet weight and the effect of hotel load (equivalent to the basal metabolic rate of animals). Several observations from this preliminary analysis for climb/glide operation of practical vehicles were made. Over a practical and useful range of hotel loads and net vehicle lift-to-drag ratios, energy savings benefits relative to level flight transit from 10% to excess of 40% can be expected. This translates directly into a 10–40% increase in range if a climb/glide strategy is employed instead of level flight transit under the right operating conditions.

1. Introduction

Marine animals have been the bio-inspirational source for some novel concepts for locomotion (Anderson et al., 2000; Triantafyllou and Triantafyllou, 1995), sensing (Yang et al., 2010), and the intelligent control of undersea vehicles (Low and Willy, 2006; Blake et al., 2008). Other advantages of biological systems are their adaptability to changes in environment and their ability for self-repair/correction of the system. At the same time, it is important to realize that the design space of human-made systems may be different than for biological systems. Vogel (2000) provides an excellent description of the different mechanical worlds of nature and those of interest to people, and provides an excellent cautionary treatise regarding taking concepts of biomimetics too far.

The goal here is not to prove general benefits of biological systems. Rather the goal is to investigate the usefulness of a specific bio-inspired concept of operation. There has been little research in the specific application of bio-inspired energy utilization strategies for undersea vehicles. There are reasons why some fish swim at an optimal cruise speed (Weihs, 1973a); and why some fish first accelerate to higher speeds, and then coast (Weihs, 1974; Videler and Weihs, 1982). Of particular interest here is why some negatively buoyant fish alternately glide downward, and then swim upward (Rayner, 1985; Rayner et al., 2001). Very similar intermittent strategies involving bounding, undulating, and chattering flight patterns have been observed with birds. These are shown in Fig. 1. The question addressed here was; can a **climb/glide** type of transit strategy be used by human-made vehicles? The answer was affirmative over a large practical design space of vehicle parameters.

The key enabler of the intermittent burst-coast and climb-glide behaviors is that the drag experienced by animals during propulsion is greater than drag experience by these animals during coasting/gliding. This is because the lift-based swimming methods used by these animals produces lift-induced drag and can cause overall drag in excess of 2–3 times that of a non-swimming animal (Weihs, 1974; Videler and Weihs, 1982). The climb-glide behaviors appear to be a result of instinctive strategies for energy use minimization. It seems reasonable that some of these strategies may be adopted by autonomous undersea vehicles (AUVs) to increase range, increase on-station time, or improve some other performance metric. The ability to accomplish this with bioinspired AUVs (like "Robotuna" (Triantafyllou and Triantafyllou, 1995)) appears promising; the ability to accomplish this goal with more traditional, rigid AUVs that use rotating propulsors is less clear.

E-mail address: nfn8960@gmail.com.

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Nomenclature

English

a	Velocity exponent in drag expression
AC	Cross-sectional area
AR	Wing aspect ratio
A_W	Vehicle wetted area
b	Wing span
c	Airfoil chord length
C_D	Drag coefficient
C_{D_AC}	Drag coefficient based on cross-section area
C_{DF}	Skin friction drag coefficient
C_L	Lift coefficient
C_T	Thrust coefficient
d	Vehicle diameter
d_B	Diameter of truncated base
D	Drag
e	Deviation from elliptical lift (~0.9)
E	Energy
$E'''_{Energetics}$	Energy density of vehicle energetics
F_W	Vehicle wet weight
h	Depth excursion
L	Lift
L^*	Vehicle length
n	Number climb/glide excursions
P	Power
P_H	Hotel power load
P_S	Shaft power
Ra	Range
s	Horizontal distance
S	Wing planform area
t	Time
T	Thrust
Ra	Range
u	Velocity
$\overline{u}, \overline{\overline{u}}$	Normalized velocity (by glide velocity)
V	Volume

Greek

α	Velocity exponent in efficiency eqn
α_I	Induced angle of attack
α_O	Geometric angle of attack
β	Coefficient in efficiency eqn
ΔE	Energy penalty – due to wing stow
$\Delta \dot{E}$	Power penalty – due to wing stow
ΔV	Volume penalty – due to wing stow
η	Efficiency
θ	Descent angle
κ	Ratio of propelled to gliding drag
λ	Lift to drag ratio
ρ	Seawater density
σ	Ratio of velocity to max range velocity
τ_D	Time duration
ϕ	Climb angle
ψ	Dimensionless hotel load parameter
Ψ	$\psi\, C_D/2$

Subscripts

Act	Actuation
C	Climb
CG	Climb/glide
Eff	Effective
g	Glide
H	Hotel
I	Induced
Max	Maximum
P	Propulsor
Prop	Propulsion/swimming
S, SS	Steady-horizontal
W	Work
T	Thermodynamic
Wing	Of the wing

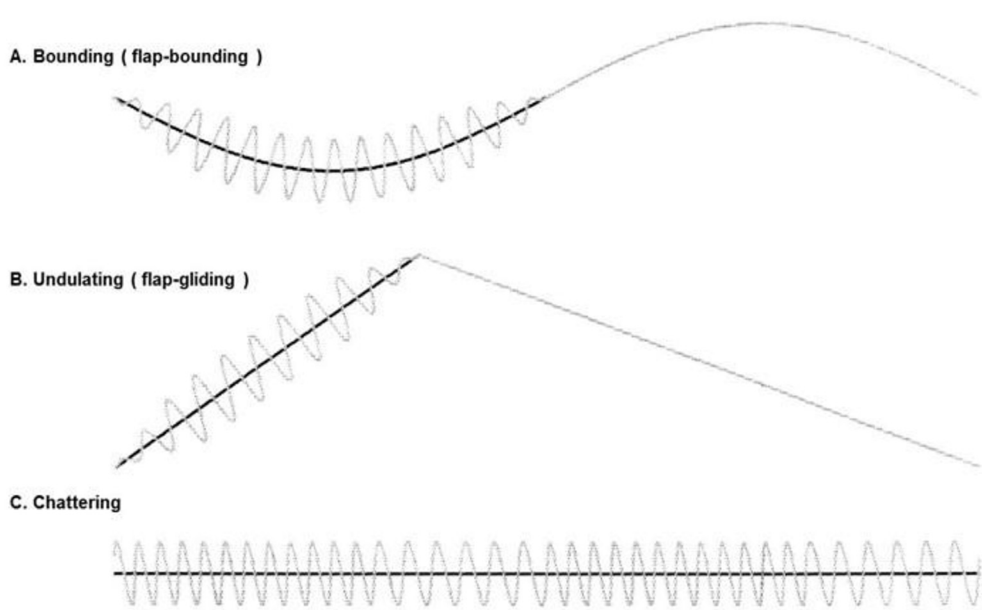

Fig. 1. Intermittent biomimetic flight strategies observed with birds (from Rayner (Rayner, 1985)).