International Journal of Non-Linear Mechanics 46 (2011) 557–567

Contents lists available at ScienceDirect

International Journal of Non-Linear Mechanics

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

Performance improvement through passive mechanics in jellyfish-inspired swimming

Megan M. Wilson, Jeff D. Eldredge *

Mechanical & Aerospace Engineering Department, 420 Westwood Plaza, Box 951597, 48-121A Engineering IV, University of California, Los Angeles, Los Angeles, CA 90095, USA

ARTICLE INFO

Available online 21 December 2010

Keywords:
Biological locomotion
Fluid–structure interaction
Viscous vortex method
Aquatic locomotion

ABSTRACT

This computational investigation explores the effect that passively responsive components of a body can have on swimming performance. The swimmer is an articulated two-dimensional system of linked rigid bodies that is prescribed with a reciprocating shape change loosely inspired by jellyfish mechanics. The six constituent hinges can be either actively controlled by fully prescribing the kinematics, or passively responsive by substituting a torsion spring in place of an actuator. The computational solver is a high-fidelity viscous vortex particle method with coupled fluid-body interactions. The prescribed kinematic Reynolds numbers involved in this investigation fall within the range 70–700. Several configurations are explored, including cases with passively responsive hinges and cases in which pairs of the hinges were held in a rigid locked position. Certain choices of passive structure lead to optimal swimming speed and efficiency. This is elucidated by a simple model, which shows that optimal performance is obtained through a balance of maximized deflection of peripheral bodies and phasing that draws benefits from both reactive and resistive force mechanisms. A study is also made of an inviscid swimmer but, due to the reciprocating kinematics of the system, the swimmer is unable to achieve meaningful locomotion, showing that vortex shedding is essential to break the symmetry of the kinematics.

1. Introduction

Creatures immersed in fluids often make use of flexibility to aid in locomotion. For example, in insect flight, wing pitch reversal at the end of a stroke is aided by passive mechanisms including aerodynamic torque and the inertia of the wing itself rather than being fully actively controlled by muscles [1,2], and in some optimized instances the wing pitch reversal was found to be entirely passive. Eldredge et al. demonstrated that a wing with chordwise flexibility is less sensitive to the phase between pitching and heaving compared to a rigid counterpart, but that performance of the flexible wing can be adversely affected by premature shedding of the leading-edge vortex [3]. Using a similar system, Vanella et al. showed that aerodynamic performance is enhanced as the linear flapping frequency approaches one of the non-linear frequencies of the flexible system [4].

For swimmers, the effects of passive flow control have been investigated in relation to the morphology of the body itself [5,6]. There have also been studies looking into the active deformation of an elastic fin under external loading by the surrounding fluid [7]. However, few have attempted to determine the energy savings that can be obtained through elastic strain energy stored in the system. Biological swimmers are known to take advantage of energy savings obtained through the elastic response of tendons and muscular tissues [8]. The flexible flukes of dolphins and whales are known to increase swimming performance [9,11]. In a spirit of abstraction similar to the present study, Kanso and Newton recently explored passive locomotion in a perfect fluid by a system of masses connected by linear springs [10].

Oblate medusan swimmers have been the target of many recent investigations, both experimental [12–18] and computational [19–22]. Such swimmers are composed of muscular filaments that circumscribe the body [23,24]. Power is delivered from the muscles during contraction, during which elastic strain energy is stored and is released during the refilling portion of the cycle [25]. It has been shown that jet-powered invertebrates use elastic springs in parallel with muscular tissues to power half of their locomotor cycle [26,27].

It is of interest to distill these biological problems into simplified mechanical problems that can more easily be studied. The passive flapping of a flag has been the subject of several recent investigations [28,29], and serves as a useful model with which to understand energy extraction from a uniform free stream. The drag reduction achievable from an elastic structure has been studied by examining the bending of a flexible filament normal to a uniform flow [30,31].

In this work, we explore an abstracted two-dimensional swimmer whose mechanics are loosely inspired by an oblate medusa. We forego any attempt to model the structure of the creature precisely, but focus instead on a two-dimensional system of linked

* Corresponding author. Tel.: +1 310 206 5094; fax: +1 310 206 4830.
E-mail addresses: meganwils@ucla.edu (M.M. Wilson), eldredge@seas.ucla.edu (J.D. Eldredge).

0020-7462/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijnonlinmec.2010.12.005