Journal of Theoretical Biology ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Theoretical Biology

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

Drafting mechanisms between a dolphin mother and calf

Kourosh Shoele [a,*], Qiang Zhu [b]

[a] Department of Mechanical Engineering, Johns Hopkins University, Baltimore, MD 21218, United States
[b] Department of Structural Engineering, University of California, San Diego, La Jolla, CA 92093-0085, United States

HIGHLIGHTS

- We model the drafting mechanism between a dolphin mother and calf beneath the free surface.
- We examine how formation pattern changes the hydrodynamic forces as well as the drafting efficiency of the calf.
- A newborn calf hydrodynamically benefits by swimming close to the free surface in the neonate position, slightly above its mother flank.
- A mother increases her swimming speed after the birth to prevent separation of her calf.
- We quantitatively show why older calves more routinely swim in the infant position than the echelon position.

ARTICLE INFO

Article history:
Received 28 October 2014
Received in revised form
14 April 2015
Accepted 16 July 2015

Keywords:
Cetacean locomotion
Formation swimming
Numerical simulation

ABSTRACT

We numerically study the drafting mechanisms between a dolphin mother and her calf swimming near the free surface. Formation locomotion between the cetacean mother-calf pair provides a way for the mother to assist the calf in its locomotion. Depending on the age and size of the calf, it swims at neonate, echelon, and infant positions. At each position, the effects of the calf's size, swimming speed, proximity to the free surface and the formation pattern are investigated and the optimal configurations predicted by the model based on the swimming hydrodynamics are compared with previous observations. It is shown that the neonate position is the optimal formation for controlling the separation of the calf, and the echelon position is the most hydrodynamically efficient position in transferring the thrust force from the mother to the calf. The infant position, on the other hand, avoids the energy loss due to wave generation so that it improves the self-propulsion performance of an older calf.

Published by Elsevier Ltd.

1. Introduction

Formation locomotion is ubiquitous in aquatic and aerial animals. It serves two primarily functions, social (Hamilton, 1967; Pitcher et al., 1982, 1976) and energetic (Breder, 1965; Lissaman and Shollenberger, 1970; Fish and Lauder, 2013). Hereby the energetic advantages are the results of hydrodynamic/aerodynamic interactions between members within a formation.

There are evidences that despite their own limited swimming capability during postnatal development, dolphin calves may benefit from their hydrodynamic interaction with their mothers and be able to sustain long-distance swimming (Norris and Prescott, 1961; Lang, 1966; Noren et al., 2008). The hydrodynamic interaction between a dolphin calf and its mother is extremely complicated, as it involves unsteady motion of two flexible bodies of different sizes at variable speeds and relative positions between them. The free-surface effect may also play a role.

Depending on the calves' ages and types of locomotion, they choose three primary positions with respect to their mothers (Fig. 1). The first one is the 'neonate position', referring to the swimming position of a newborn calf close to its mother (slightly above her flank). It was speculated that this position is due to the lack of ability of newborn calves to fully control their buoyancy (Edwards, 2002). In addition, the newborn dolphin calf has a poor control of directional responses, causing it to collide with tank walls or to get itself stranded in shallow areas (Reid et al., 1995). It is observed that the mother dolphin increases its swimming speed immediately after birth while keeping the neonate on her flank close to her body (Chirighin, 1987; Tayler and Saayman, 1972; Mann and Smuts, 1999). The first surfacing of the calf after its birth, facilitated by the positive buoyancy force of its own body, usually happens without the assistance of the mother (Edwards, 2002; Cockcroft and Ross, 1990). In the subsequent surfacing for breaths, however, there is a close synchrony between mother and calf.

Within a few hours after birth, the calf relocates to another position called 'echelon position', which is within 10 cm of the mother's flank and close to the mother's dorsal fin (Cockcroft and

* Corresponding author. Tel.: +1 858 539 6818; fax: +1 858 822 2260.
E-mail address: kshoele@jhu.edu (K. Shoele).

http://dx.doi.org/10.1016/j.jtbi.2015.07.017
0022-5193/Published by Elsevier Ltd.

List of symbols

U	swimming speed
t	time
g	gravitational acceleration
D	submergence of the mother (draft)
L	length of the mother
l	length of the calf
W	size of computational domain in X and Y
X,Y,Z	Cartesian coordinates
ω	angular frequency of oscillation
f	$\omega/2\pi$
$A_{\max}$	maximum backbone deflection of the mother
$\alpha_{\max}$	maximum pitch angle of fluke
β	l/L
V_{b1},V_{b2}	velocities of the mother and calf
Φ	velocity potential
ϕ_b	velocity potential caused by the body
ϕ_w	velocity potential caused by the wake
ϕ_f	velocity potential caused by the free surface
μ_w	dipole strength of the wake
S_{b1}	body surface of the mother dolphin
S_{b2}	body surface of the calf
S_w	wake sheet
S_f	free surface
$\bar{S}_f$	mean free surface
ξ	free-surface elevation
F_1, F_2	total hydrodynamic force on the mother and calf
$\bar{F}_x$	mean thrust force in the direction of U
ρ	density of fluid
C_S	suction coefficient
C_P	coefficient of power consumption
C_T	mean thrust coefficient

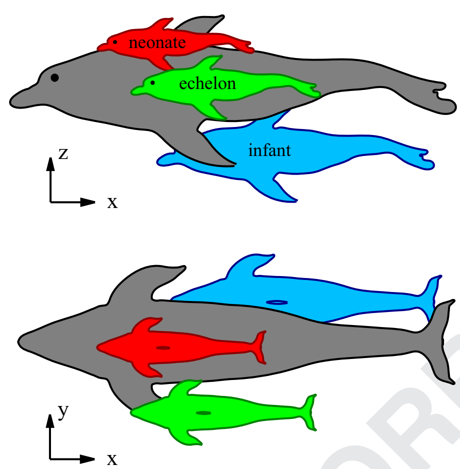

Fig. 1. Side view (upper figure) and top view (lower figure) of the swimming positions of a dolphin calf in relation to its mother.

Ross, 1990; McBride and Kritzler, 1951; Wells, 1991). In the vertical direction, the calf's body is placed near its mother's upper- or mid-body (Reid et al., 1995; Mann et al., 2000). Although the exact hydrodynamic function of this formation is not known, it does appear that the calf may utilize a drafting mechanism to gain some hydrodynamic advantages by moving along its mother (Weihs, 2004). This permits neonates to maintain high speed with reduced tailbeating (Norris and Prescott, 1961).

As a cetacean offspring grows in size, there is a tendency for its mother to prevent it from swimming in the echelon formation (Mann and Smuts, 1999; Taber and Thomas, 1982). Instead, older calves mostly swim under the mother's tail section at very close proximity. This position is known as the 'infant position'.

It is observed that in the first 2 weeks of a calf's life, it swims almost entirely in the echelon position. Within the first month of its life, the echelon position dominates (between 70% and 100% of swimming time) while the infant position occupies less than 10% of the swimming time (Mann and Smuts, 1999; McBride and Kritzler, 1951; Gubbins et al., 1999). By the second or third month, calves swim in echelon position about 50% of the time and in infant position about 20–50% of the time. Reid et al. (1995) observed that there was also a gradual increase in the calf-mother distance during the second month of the infant's life. During month 3 to 6, swimming in echelon position decreases to about 40% of the time while swimming in infant position increases to about 30% of the time (Reid et al., 1995). Later, after about 6 months of age, although the synchronized swimming between dolphin mother and calf happens only 10% of the time, the calf still spends most of its time near its mother with about 30% in echelon and 35% in infant positions.

There are only a few papers studying the hydrodynamic advantages of drafting. In an early work by Kelly (1959), it was assumed that the flow could be described by the classical solution of two identical spheres moving at the same speed. It was shown that it is possible for one sphere to create a pressure field and cause the drafting of the other. Weihs (2004) modeled the hydrodynamic interaction between a mother and calf as the interaction between two ellipsoids in potential flow, and observed that in certain positions the calf gains positive thrust force from the pressure field created by its mother. Since these studies assumed simple axisymmetric geometries for the dolphins, they only discussed trends of the drafting force at different longitudinal and radial positions of the calf with respect to the mother and ignored the effects of the free surface, circumferential placement of the calf and the undulatory motions of the dolphin mother and calf.

In this study we employ a potential-flow-based approach to investigate the hydrodynamic interactions among the mother, the calf, and the free surface at different conditions. Compared with previous studies, a much more sophisticated model is employed, in which the realistic geometry of dolphin bodies, the undulatory motions of the bodies and the flapping motions of the tail, and the free-surface effect are all accounted for. The purpose is to quantitatively illustrate the drafting effect and its significance to the locomotion of the calf.

It is necessary to point out that in general, animal behavior in nature is driven by various factors and mechanics is only one of them. To eliminate any prejudgment in our study, we only present characteristics and possible advantages in hydrodynamics at different positions, which may prove to be useful evidence for biologists for further investigation.

The rest of the paper is organized as following. We start by creating a physical model which includes the geometries and kinematics of the mother and calf. The mathematical formulations and numerical algorithm will then be briefly described. In the results session, we will conduct systematic numerical simulations of the pair swimming at different speeds and positions. Different calf sizes will also be considered. The concentration will be the drafting thrust effect (which help the calf in its locomotion) and the suction effect (which keeps the calf from drifting away from its mother). Finally, conclusions are drawn.

Please cite this article as: Shoele, K., Zhu, Q., Drafting mechanisms between a dolphin mother and calf. J. Theor. Biol. (2015), http://dx.doi.org/10.1016/j.jtbi.2015.07.017