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The effects of a longfin inshore squid's fins on propulsive efficiency during underwater swimming

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ABSTRACT

Underwater transportation has always been attractive for human beings. Especially, the design of an underwater vehicle with high propulsive efficiency has become a passion for many researchers and engineers. While the design of such a vehicle has been discussed for a long time, an aquatic animal, namely a longfin inshore squid, has been exhibiting an incredible swimming performance under water for centuries. In this study, a longfin inshore *doryteuthis pealeii* squid was scanned using computer tomography (CT) to capture the details of the squid's geometrical appearance. In addition, a three-dimensional model of the squid has been built with computational fluid dynamics to understand the swimming technique of a squid. Propulsive efficiencies of squid models were calculated for 0°, 4° and 8° angles of attack, funnel diameters of 0.25 cm, 0.5 cm and 1 cm and Reynolds numbers of 4.6E5, 1.0E6 and 1.6E6. A longfin inshore squid illustrated nearly 80% propulsive efficiency when the model had no fins at 0° angle of attack with 1 cm funnel diameter. Therefore, it was noted in this study that the use of larger funnel diameter, swimming with a smaller angle of attack and absence of fins provided better propulsive efficiency.

1. Introduction

Underwater locomotion in submarines, ships and remotely operated vehicles (ROVs) have attracted many researchers' attention. The design of these vehicles is mainly twofold. While the body shape is directly associated with the drag the vehicle experiences, thrust on these vehicles is provided by propellers and the fins are responsible for steering and lift production on these vehicles. Besides, typical underwater propulsion can be created by propeller systems although the engine the propeller system uses limits the magnitude of produced thrust. Even though underwater vehicles seem to be working well, the efficiency of these propulsion systems have usually been questioned because there have been discussions about the efficiency of steady jets over unsteady jets. In nature, when a movement of birds and fish is observed, locomotion of these creatures is mainly based on a flapping wing or a fin (Drucker and Lauder, 1999, 2001; Hedenstrom and Spedding, 2008). While this type of locomotion is generated due to unsteady flow, the ejection of pulsed jets by a squid and a salp also benefit from unsteady fluid flow propulsion questioning advantages of unsteady fluid flow efficiency over steady fluid flow efficiency (Linden, 2011). In fact, the first experimental verification was provided by Ruiz et al. (2011) who stated that pulsed propulsion could be more efficient than a steady jet. They performed simultaneous measurements of flow power consumption on a self-propelled body and a normalized power consumption coefficient was calculated for both pulsed and steady propulsors. A significant increase in propulsive efficiency of unsteady flow compared to steady flow was documented and an increase in propulsive efficiency was discussed with the help of vortex added mass and entrainment. Therefore, researchers have been looking for ways to improve propulsion systems for underwater vehicles. Furthermore, since water has a much larger density and viscosity than air, underwater locomotion faces challenges on drag forces acting on these vehicles. Besides, submerged vehicles typically use water tanks like ballast tanks for diving and surfacing and the vehicle's weight is generally supported by buoyancy. However, these vehicles possess fin shape diving planes at the front and/or back of the vehicles to provide positive or negative lift. Therefore, a good design of an underwater vehicle can help to improve the efficiency of an underwater locomotion. While engineers have been evaluating the propulsion efficiencies of these vehicles, squids have been presenting an incredible ad hoc propulsion mechanism in nature. These aquatic creatures have quick maneuver abilities and create a high thrust force though their funnels. Basically, squids having a streamlined body make underwater locomotion possible by unsteadily ejecting the water while they typically use their fins for slow swimming, steering, and producing lift although some squids may not possess fins on their body. In the literature, Blake

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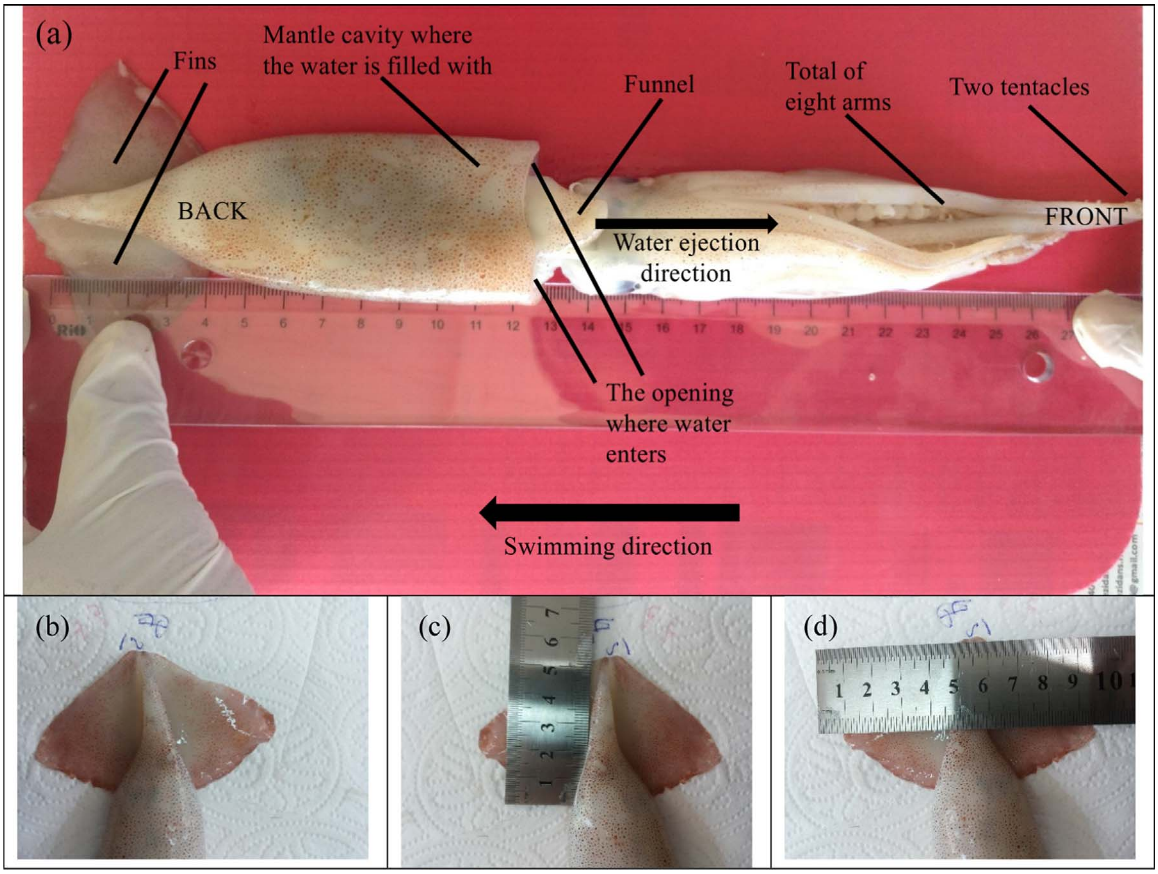

Fig. 1. Anatomy of a longfin inshore squid (a), the fin of a longfin inshore squid (b), leading edge (c), and wingspan (d) of the squid's fins.

(1981) experimentally investigated the effect of pectoral fin shape on thrust and drag in labriform locomotion. A variety of fin shapes including square, rectangular and triangular were studied and it was noted that pressure drag of triangular fins were 14% larger than of square and rectangular fins for the same wetted area. O'dor (1988) studied cine films of *Loligo opalescens* berry swimming speeds from 0.1 to 0.5 m/s in a tunnel. He estimated all the forces on horizontal and vertical planes and he realized that fin thrust was significant only for slow swimming (i.e., below 0.2 m/s). It was noted that 30–90% of the total force was associated with hydrodynamic lift production for negative buoyancy during forced swimming in the tunnel. Anderson and Demont (2005), Anderson and Demont (2005) investigated *Doryteuthis pealei* squid fins from a locomotory function point of view. They collected high spatial and temporal resolution kinematic data to analyze the role of fins in squid locomotion during steady swimming in a flume. They noted that the *Doryteuthis pealei* squid's fins showed wave-like and flapping wings behaviors at low and high speeds, respectively. They also documented that fins were capable of producing thrust based on the analysis of fin wave speed, angle of attack and body acceleration. Anderson and Grosenbaugh (2005), Anderson and Grosenbaugh (2005) studied a squid's jet propulsion system and they explained the use of the squid's fins and mantle cavity for slow swimming and jet propulsion, respectively. The acceleration phase of a squid's jet propulsion was discussed and it was noted that a squid can reach high speeds under water in a short period of time and this ad hoc system helps to control the dynamic balance of swimming at different speeds by activating the fins and / or mantle cavity. In another study, fin wake patterns and forces produced by fins of *Lolliguncula brevis* were investigated by Stewart et al. (2010) experimentally. Hydrodynamic fin data were studied from 18 swimming *Lolliguncula brevis* squids. They reported that fins were able to generate both horizontal and vertical direction forces at different swimming speeds and orientation based on two-dimensional DPIV. It was noted that four distinct fin wake structures were identified with a variety of vortex patterns. Wake patterns also implied that locomotive force generation was possible with fins. They also stated that squid fins were primarily responsible for lift while thrust generation was secondary during arms-first swimming of *Lolliguncula brevis* squids. An autonomous underwater vehicle (AUV) was experimentally and numerically evaluated by Mansoorzadeh and Javanmard (2014). While their goal was to reveal the effect of free surface on the AUV's hull, their model had a rudder fin at the bottom to provide vertical control and two horizontal stern fins at the sides to have maneuverability. In their study, the AUV model was placed at different depths from the free surface and the nominal speed of the model was varied between 1.5 m/s and 2.5 m/s to investigate the effect of AUV speed on drag and lift forces along with the coefficient of drag and lift. Finally, they compared their numerical findings with experimental results obtained from a towing tank setup using a 1:1 scale model. Recently, Malazi and Olcay (2015) studied two-dimensional axisymmetric squid models at various Reynolds number and different fineness ratios. The two-dimensional axisymmetric squid simulations were performed with Ansys-Fluent. The drag coefficients and required jet propulsive forces for moving forward were evaluated at various swimming speeds. More recently, Malazi and Olcay (2016) numerically investigated the forces acting on a simplified two-dimensional axisymmetric *Doryteuthis pealeii* squid model during an unsteady acceleration. They calculated the basset and added mass forces and they reported that a least thrust force was needed for the modified squid model during the acceleration phase of the time dependent velocity profile compared to the other models studied.

In this study, three-dimensional squid models with and without fins were investigated to understand the effects of fins on lift and drag forces at various angles of attack and steady swimming velocities. The present study assumed that fins in the numerical models were rigid and