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Dynamics of prolate jellyfish with a jet-based locomotion

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ABSTRACT

Swimming jellyfish deliver momentum to the surrounding fluid in the form of vortices. A three-dimensional computational model was adopted to investigate the characteristic flow patterns produced by jellyfish with a jet-based locomotion and the process of vortex generation. The interaction between jellyfish and the surrounding fluid may be simulated using the immersed boundary method. The vortex structures generated in the wake were elucidated in detail. The vortices were formed due to the contraction and expansion of the elastic bell. A dimensionless temporal parameter was employed to analyze the vortex formation process. During the early stage of contraction, the vortices were dominantly generated by the stroke. The ejected fluid from the inside of the bell was then entrained into the vortices, thereby decreasing the vorticity at the core and increasing the total circulation within the vortex ring. The Froude propulsion efficiency increased as the vortex formation number increased, implying that the propulsion in the way of growing the vortex structures was favorable in terms of the efficiency.

1. Introduction

The hydrodynamic patterns present in the wakes of swimming or flying animals are fluid dynamic footprints generated by the interactions between the animals and the surrounding fluid. Momentum is transferred from an animal to the surrounding fluid, giving rise to hydrodynamic patterns in the wake. Newton's second and third laws hold that the locomotive force exerted on an animal by the fluid is equal in magnitude to the rate at which the momentum is transferred to the fluid by the animal (Dabiri, 2005). The properties of the hydrodynamic patterns present in the wake, therefore, have been extensively studied as a means for inferring the locomotion mechanisms, including the magnitude and direction of locomotive force, underlying biological propulsion systems (Dabiri, 2005).

In biological propulsion, animals often transfer momentum to the surrounding fluid in the form of vortex. Many researchers have quantitatively explored the phenomena related to vortex formation processes and defined the vortex formation time as the length-to-diameter aspect ratio of the fluid plug injected from the nozzle (Dabiri and Gharib, 2005; Gharib et al., 1998; Mohensi et al., 2001). The vortex formation number is not the number of generated vortices, but the value of the vortex formation time, beyond which the leading vortex ring ceases to grow and is disconnected from the trailing jets (Gharib et al., 1998). The vortex formation time was also defined for a flow through nozzles with a temporally variable exit (Dabiri and Gharib, 2005). Krueger and Gharib (2003) experimentally found that the normalized time-averaged thrust per jet pulse reached the maximum value when the dimensionless vortex formation time was approximately 4.

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Indeed, an optimal vortex formation was closely related to the propulsion kinematics such as speed, thrust, or propulsion efficiency in biological propulsions (Dabiri, 2009; Linder and Turner, 2004). Hence, the investigation of kinematics in the vortex formation process can provide a potential optimal design for engineering propulsion systems as well as help understanding the propulsion mechanism.

Jellyfish are one species delivering momentum to the surrounding fluid in the form of vortices. Jellyfish can be classified based on their swimming mechanism. Some planktonic medusa, termed the 'jetters', mainly swim via a jet mechanism in which the locomotive thrust is derived from a subumbrella volume change that occurs during the power and recovery stroke (Colin and Costello, 2002). These taxa generally assume a prolate bell morphology and leave a clear jet structure with a single vortex ring called a 'starting vortex' in their wake (Colin and Costello, 2002). Other species, termed 'rowers', have generally oblate bell morphologies and generate "starting/stopping" vortices during the contraction/relaxation phases, respectively (Colin and Costello, 2002; Costello et al., 2008; McHenry and Jed, 2003).

The hydrodynamics of the wake are intimately associated with the swimming patterns determined by the stroke duration and pulse interval. An appropriate swimming pattern was chosen by jellyfish according to circumstances such as traveling, fishing, or escaping (Megill, 2002; Mills, 1981; Park et al., 2014). Many dynamic models have been proposed for predicting the kinematics of swimming jellyfish (Daniel, 1985; Colin and Costello, 2002), although the hydrodynamics in the wake has not been considered in these models. Numerical studies have been performed to visualize the wake structures produced by swimming jellyfish and to elucidate related phenomena. Rudolf and Mould (2010) applied a semi-Lagrangian method with immersed boundary conditions to describe the motions of swimming jellyfish numerically using a spring-mass system. By using the immersed boundary method (Peskin, 2002), Herschlag and Miller (2011) used the bell model of a simplified jellyfish and investigated the effective limits of jet propulsion in terms of the Reynolds number. Park et al. (2014) adopted an immersed boundary method to elucidate the hydrodynamics in the wake and the propulsion kinematics of an oblate jellyfish implementing a paddling-based locomotion. The thrust-generating mechanisms in both prolate and oblate jellyfish were investigated by using the arbitrary Lagrangian–Eulerian (ALE) formulation (Sahin and Mohseni, 2009; Sahin et al., 2009). Alben et al. (2013) performed numerical simulations using an analytical model to study the relationship between the kinematics and the performance of jellyfish with a jet-based locomotion. Although extensive numerical studies have been performed to visualize the hydrodynamic patterns of swimming jellyfish, few studies have focused on the vortex formation process and the related kinematics such as vorticity or circulation. Also, for a prolate jellyfish with a jet-based locomotion, the relations between the optimal vortex formation and propulsion kinematics such as speed or efficiency have not been elucidated.

In the present study, the dynamics of jellyfish with a jet-based locomotion in a quiescent fluid were explored. The objectives of the present study were to examine the vortex formation process and measure the vorticity and circulation during the vortex formation process. By a quantitative approach, the relations between the vortex formation and the Froude propulsion efficiency were elucidated from the view point of the vortex formation time, providing a better understanding of the optimal vortex formation in the propulsion systems. The interactions between the surrounding fluid and the swimming jellyfish were derived in the framework of the immersed boundary method, in which the momentum forces due to the interactions were added to solid and fluid governing equations. Section 2 describes the formulation and numerical methods used to simulate a swimming jellyfish in a quiescent fluid. The numerical results and discussion are explored in Section 3. Finally, a summary is presented in Section 4.

2. Problem formulation

We simplified the jellyfish morphology using an ellipsoid bell model with a measurable fineness ratio determined by the height divided by the diameter of the bell. The contraction/relaxation phase was followed by a power/recovery stroke in the jellyfish bell. The bell was composed of an elastic material, by which the bell experienced a passive relaxation behavior derived from the elastic energy stored during the contraction phase (Megill, 2002). We mimicked a swimming jellyfish named *Sarsia* sp. and set the fineness ratio to 1.0. Fig. 1(a) shows a schematic diagram of the fluid domain and the jellyfish bell. In the framework of the immersed boundary method (IBM), the momentum forcing term arising from the interactions between the surrounding fluid and the jellyfish was added to each governing equation. These governing equations were coupled by the momentum forcing term in the IBM.

The Lagrangian variables (s_1, s_2) in the solid motion equation were defined on a moving curvilinear grid system. The position of the jellyfish body, denoted as $\boldsymbol{X}(s_1, s_{2,}\ t)$, obeyed the equation

$$\rho\frac{\partial^2 \boldsymbol{X}}{\partial t^2} = \boldsymbol{F}_e - \boldsymbol{F}_l + \boldsymbol{F}_b, \tag{1}$$

where ρ indicates the additional boundary mass, which is the difference between the densities of the solid and the fluid, $\boldsymbol{F}_e$ is the elastic force term that reflects the elastic properties of the jellyfish bell, $\boldsymbol{F}_l$ is the Lagrangian momentum force obtained as a result of fluid–membrane interactions, and $\boldsymbol{F}_b$ denotes the body force required to deform the bell during the contraction period. $\boldsymbol{F}_e$ was derived from the variational derivative of the energy function. The strain energy density used in the present simulation was equivalent to the Skalak law by neglecting the area dilation effect. The stress tensor can be obtained by $\partial W_s/\partial D_{ij}$ and takes the form of $\sigma_{ij} = 2\phi_{ij}D_{ij}$, where W_s denotes the strain energy density, D_{ij} the green strain tensor, σ_{ij} the stress tensor and ϕ_{ij} indicate the stretching coefficient for $i = j$ and the shearing coefficient for $i \neq j$. The subscripts 'i' and 'j'