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Low Reynolds number swimming of helical structures in circular channels

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ABSTRACT

Rotating helical structures are very effective in low Reynolds number swimming and propulsion. Helical rods are extensively studied theoretically and computationally with asymptotical methods, but the effects of the geometric variables in full-scale and the performance of other helical structures, such as ribbons and Archimedean screws, are also important for the understanding of swimming in confinements and design of micro swimming robots. In this study, a CFD model is developed to study swimming of helical rods, ribbons, screws and filaments, in circular channels under constant angular velocity or constant external torque. Effects of geometric parameters and the confinement radius on the swimming velocity and efficiency are demonstrated. Wavelength and amplitude of the helical wave, filament radius, thickness and width of ribbons, and eccentricity of tails are studied. Swimming performance of magnetically coated ribbons is compared with the ribbons with magnetic heads. Theoretical results in literature are used to validate the CFD results and to identify the role of hydrodynamic interactions between helical body and the channel wall.

1. Introduction

Artificial micro swimmers (AMS) present a huge potential for medical applications, such as drug delivery and minimally invasive surgical operations (Nelson et al., 2010; Sitti et al., 2015; Feng and Cho, 2014; Yan et al., 2015; Qiu and Nelson, 2015). Various approaches for the design of AMS are inspired by micro organisms, such as bacteria or spermatozoa, that move by means of beating or rotary motion of cilia and flagella in aqueous solutions (Brennen and Winet, 1977; Elgeti et al., 2015; Lele et al., 2015). Advances in fabrication techniques allow producing a diverse range of shapes that serve as bio-mimetic artificial propellers (Yan et al., 2015; Qiu and Nelson, 2015; Barbot et al., 2016; Beyrand et al., 2015; Huang and Mei, 2015; Zhao et al., 2003; Stanton et al., 2015; Khalil et al., 2013). External magnetic fields have been used extensively for the actuation of AMS with helical tails. Ghosh and Fischer (2009) manufactured micron long SiO_2 helical micro swimmers, actuated by Helmholtz coils and navigated to demonstrate controllable trajectories. Li et al. (2013) demonstrated the swimming of helical nanoswimmers, which are as small as 100 nm in diameter and 600 nm in length based on the electro-deposition of Pd/Cu nanorods into nanoporous membranes as described by Liu et al. (2011). Gao et al. (2013) deposited Ti and Ni layers directly onto the spiral water-conducting vessels obtained from various plants, and tested the swimming performance of these magnetically actuated helical swimmers at different frequencies using Helmholtz coils. Zhang et al. (2009) employed micro manufacturing techniques to produce 42 nm thick helical ribbons 1.8 μm in width and 49.7 μm in length. Similarly, artificial bacterial flagella of 16 μm microns in length and 5 μm microns in diameter are manufactured by Qiu et al. (2014) and

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used for temperature controlled, targeted drug administration. Maier et al. (2016) demonstrated swimming of DNA-based flagellar bundles featuring magnetic beads. In another study featuring multiple flagella, Beyrand et al. (2015) examined different propulsion modes such as tumbling, rolling, and wobbling along with the capability of the AMS in cargo transport. Lastly, magnetotactic bacteria are utilized as self-propelled natural micro robots and controlled by time-varying magnetic fields (de Lanauze et al., 2014) to perform complex micro assembly tasks (Martel and Mohammadi, 2010). Further examples on various fabrication and actuation methods of micro swimmers are reviewed by Peyer et al. (2013). Advances in drug delivery featuring artificial micro swimmers are reported by Gao and Wang (2014).

In addition to experiments that demonstrate the efficacy of helical swimming, helical tails have been studied by several authors theoretically and computationally. Sir James Lighthill's Slender Body Theory (SBT) (Lighthill, 1976) predicts the swimming velocity accurately for unconfined, infinitely long, thin helical filaments. On the other hand, Felderhof's approximate perturbative solution (APS) (Felderhof, 2010) includes the effect of confinement for infinitely long cylinders with helical perturbations, and solves for the velocity and efficiency correctly for small helical amplitudes compared to the confinement radius. Man and Lauga (2013) used resistive force coefficients to analyze the wobbling behavior of helices that rotate with an external magnetic field and showed that swimming is more efficient for larger wavelengths and number of waves due to decreasing wobbling of the swimmer. A recent study by Koens and Lauga (2016) reports the development of slender ribbon theory (SRT) and resistance coefficients for helical ribbons which are defined by two length scales for the cross-section, namely, thickness and width, for only slender geometries, whose thickness is much smaller than other dimensions.

Computational studies on helical swimmers have utilized mostly the boundary element method (BEM). Liu et al. (2014) investigated helical filaments swimming inside a circular channel with BEM by varying the helical pitch angle and the ratio of the filament thickness to the arc length of one helical turn, and reported the swimming characteristics under constant torque and constant angular velocity applications with respect to the confinement. Spagnolie and Lauga (2010) presented a numerical study to predict the optimal shape for elastic flagella of both finite and infinite sizes in terms of hydrodynamic efficiency and compared the results to Lighthill's findings on optimal flagellum (Lighthill, 1975). The authors (Spagnolie and Lauga, 2010) concluded that for infinitely-long flagella, helical shapes are the optimal in three dimensions, whereas modified saw-tooth profiles are found to be more efficient in two dimensions, which are variations on the geometries suggested by Lighthill (1975). Spagnolie et al. (2013) demonstrated that the effect of viscoelasticity on the swimming characteristics is dependent on the shape of the helical tails. Performance of confined helical tails with different cross-sections and pitch angles is studied by Li and Spagnolie (2015) to determine optimum helical shapes for efficient swimming and pumping. Montenegro-Johnson et al. (2017) developed a BEM tailored for ribbons and sheets, that accurately captures the swimming dynamics of slender swimmers with lengths comparable to their widths. Keaveny and Shelley (2011) investigated propagating helices with elliptic cross-sections by calculating the tractions on the swimmer body using numerical solutions of the boundary integral equations. Keaveny et al. (2013) also utilized the boundary integral formulations to replicate the swimming speeds measured experimentally for various helical swimmers, and suggest variations on the design (such as centerline optimization) to maximize speed. In addition to BEM, Acemoglu and Yesilyurt (2014) used a CFD model to study swimming of a model micro organism with a helical tail in cylindrical channels and reported effects of geometric parameters of the helical tail on the swimming velocity and efficiency.

In this work, effects of geometric parameters on the swimming performance of helical rods, ribbons, filaments and Archimedean screws are demonstrated; wavelength, amplitude, radius and eccentricity (for rods), confinement radius, helix thickness and width (for ribbons and screws) are included in the study. A CFD model is developed to obtain the swimming velocity, torque, angular velocity, and efficiency of the helical structures inside circular channels. First, the helical rods are discussed and the swimming velocities are compared with the SBT (Lighthill, 1976), which does not include the wall effects, and APS (Felderhof, 2010), which includes the wall effects only for small amplitudes of the helix. Comparisons also serve as a validation of the model with theoretical results. Then, ribbons and screws are discussed to demonstrate the effects of thickness and width for the structures with rectangular cross-sections. Ribbons are of particular interest due to advantages of bulk-micro manufacturing techniques in mass production of such structures, as demonstrated by Zhang et al. (2009) with the "self-scrolling helical ribbon". Effects of ribbon width are compared for the ribbons attached to a magnetic head and coated with magnetic materials. Lastly, resistance coefficients are obtained for the full experimental swimmer (Zhang et al., 2009) and compared with the experimental values and previous numerical results (Koens and Lauga, 2016; Montenegro-Johnson et al., 2017; Keaveny et al., 2013) as a validation and to understand the effects of the swimmer geometry.

2. Methodology

2.1. Governing equations and boundary conditions

Low Reynolds number swimming of helical tails is governed by incompressible Stokes equations which is given in the non-dimensional form as follows

$$-\nabla p + \frac{1}{Re}\nabla^2 \mathbf{u} = 0 \tag{1}$$

and

$$\nabla \cdot \mathbf{u} = 0 \tag{2}$$