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Simulation of Sperm-Like Microswimmers Using Finite Element Method

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ABSTRACT: This research investigates the motion of microorganisms in an incompressible Newtonian fluid using the finite element method in 2D and 3D. The undulating motion generated inside a microswimmer's tail creates hydrodynamic forces within the fluid, which its reaction force propels the microswimmer forward. The Navier-Stokes equation is coupled to Newton's law and solved in the computational domain to simulate the microswimmer's motion. In the first part of this study, the effect of geometric parameters (channel width) and wave parameters (wave amplitude and wavelength) on the swimmer's velocity was investigated. The obtained results indicated that the trend of velocity changes in 2D is not predictable, and the channel height affects this relationship significantly. In the second part of this study, the synchronized swimming phenomenon in 2D and 3D was investigated using the developed model. The results showed that the average swimming velocity in 2D side-by-side, 3D side-by-side, and 3D top-bottom configurations increases by 12%, decreases by 10%, and increases by 7%, respectively. Finally, by examining the pressure distribution in the computational domain, it can be concluded that the force dipoles created by the microswimmers' undulating tails, and their position, are the reason behind the increase or decrease of the average swimming velocity.

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1- Introduction

Decades ago, Taylor [1] (analytical) studied the swimming motion of an infinite sheet with low amplitude sinusoidal beating waves in a viscous fluid, similar to beating waves in a spermatozoon flagellum. He solved the Stokes equation and showed that the sheet moves forward at a rate of $2\pi^2 A^2/\lambda^2$ times the propagating wave speed. Hancock [2] (analytical) introduced the basics of a Slender Body Theory. He put distributions of force functions (Stokeslets and dipoles) capable of generating the equivalent effect of an undulating filament inside the fluid domain to imitate the swimmer's motion. He showed that the motion of a finite filament and an infinite sheet, both moving with the same wave parameters, are not very different.

Also, remarkable and surprising results were obtained over the years by examining microorganisms such as sperm and bacteria. Two interesting features of sperm swimming are slithered and synchronized swimming. The point to consider about synchronized swimming is the existence of different results obtained from analytical, experimental, and numerical research. Gompper et al. [3] (numerical) investigated the synchronization phenomenon of sperm clusters containing up to 20 sperms. They showed that the dissipated energy rate for synchronized swimming decreases when the tails beat in phase. Woolley et al. (experimental) [4] observed flagellar synchronization between bull spermatozoa as they swam in a viscous medium. They also observed a rise in conjoint beat frequency, wave velocity, and swimming velocity in paired spermatozoa.

Against the cases mentioned above, some studies reported that not only does not side-by-side and in-plane synchronization increase swimming velocity, but it also decreases it and increases the average energy dissipation rate. They noted that only the above-below configuration of swimmers in the 3D fluid domain would increase velocity and decrease energy dissipation rate. Llopis et al. [5] (numerical) showed that the total efficiency increases when the swimmers are co-planar and synchronized at small distances between the swimmers. However, the opposite happens to the swimming velocity.

In this paper, we will first propose a microswimmer model in both 2D and 3D and investigate the effect of geometrical and wave parameters on its swimming speed. In the second part, synchronized swimming in different configurations is examined using the developed model.

2- Results and Discussion

In this section, the present study is first validated against the works done by Katz [6] and Qin et al. [7], then results obtained in the simulations are presented.

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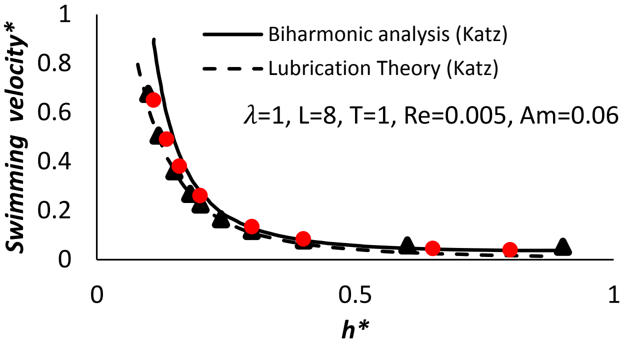

Fig. 1. Validation of the present model compared with the results of Katz [6] and Qin et al. [7].

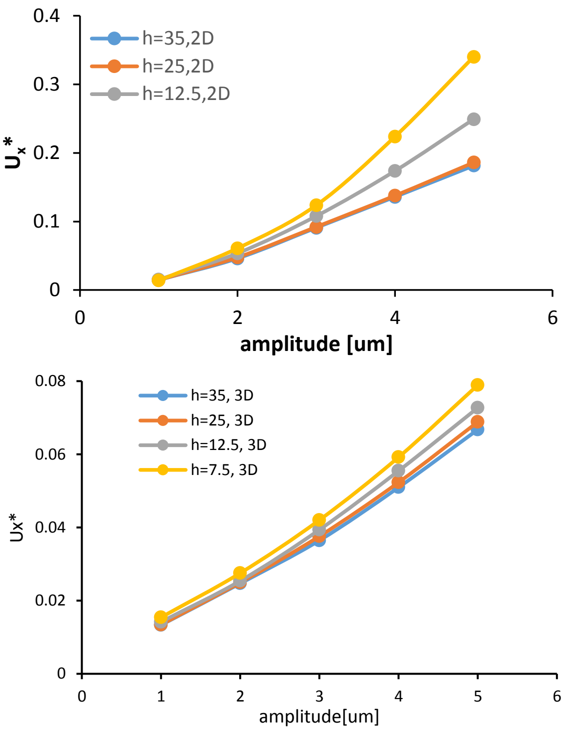

Fig. 2. Changes in the magnitude of the dimensionless swimming velocity inside microchannels with different widths, based on the amplitude of the wave created inside the swimmer's tail. Top: 2D, Bottom: 3D

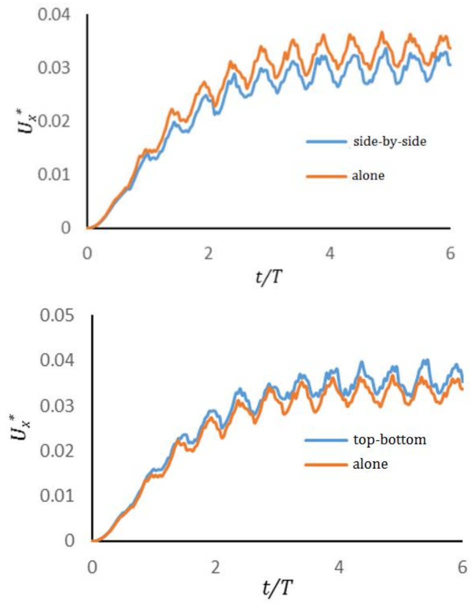

Fig. 3.Top: Dimensionless swimming velocity for side-by-side and single swimming configurations in 3D, bottom: Dimensionless swimming velocity for side-by-side and single swimming configurations in 3D

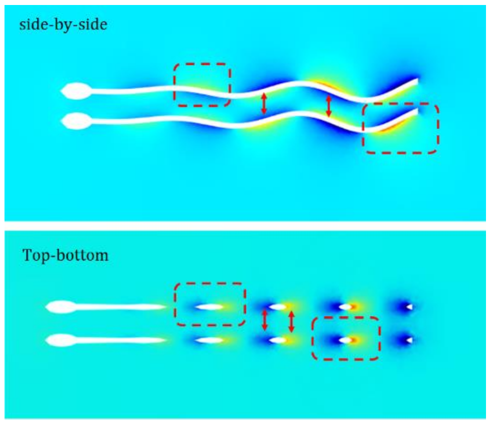

Fig. 4. Pressure dipoles caused due to the microswimmers' tail motion for side-by-side and top-bottom configurations

As seen in Fig. 2, the reason behind the deviation of 2D results from the analytical correlations is that the flow is confined in 2D space, which causes unrealistic stresses to occur and increase the swimming velocity. In contrast, in 3D space, the flow can easily shift from high-pressure areas to low-pressure, causing the flow field to have a more realistic distribution and preventing excessive stresses over the swimmer's surface.

Regarding the results obtained from investigating synchronized swimming, as seen in Fig. 3, it is shown that when swimmers are placed over a shared plane and swim in side-by-side configurations, their mean swimming velocity decreases by 10 percent when compared to the swimming velocity of a single swimmer. However, in the case of top-bottom synchronized swimmers, the results show that the mean average velocity increases by 7% compared to a single swimmer. This difference is speculated to be due to the pressure distribution around swimmers.

As seen in Fig. 4, when swimmers are in a side-by-side configuration, the fluid pressure in space between swimmers negates each other causing the swimming velocity to decrease. In top-bottom, the pressure reinforces itself, causing a rise in swimming velocity.

3- Conclusions

This research simulated the swimming of microorganisms in an incompressible Newtonian fluid. The microswimmer creates hydrodynamic forces in the fluid by creating waves in its flagellum. In the first part of this research, the swimming of a single microorganism was investigated, and the effect of geometric and wave parameters on swimming velocity was investigated.

In the second part of this research, synchronized swimming was investigated. It was shown that the average swimming velocity in 2D side-by-side, 3D side-by-side, and 3D top-bottom configurations increases by 12%, decreases by 10%, and increases by 7%, respectively. Also, it was shown that the location and direction of pressure dipoles created due to the swimming of microorganisms is the reason behind this phenomenon.

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