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Numerical Study on the Flow around a Steadily Rotating Spring: Understanding the Propulsion of a Bacterial Flagellum

Won Yeol Choi, Sangmo Kang

Abstract**—**The propulsion of a bacterial flagellum in a viscous fluid has attracted many interests in the field of biological hydrodynamics, but remains yet fully understood and thus still a challenging problem. In this study, therefore, we have numerically investigated the flow around a steadily rotating micro-sized spring to further understand such bacterial flagellum propulsion. Note that a bacterium gains thrust (propulsive force) by rotating the flagellum connected to the body through a bio motor to move forward. For the investigation, we convert the spring model from the micro scale to the macro scale using a similitude law (scale law) and perform simulations on the converted macro-scale model using a commercial software package, CFX v13 (ANSYS). To scrutinize the propulsion characteristics of the flagellum through the simulations, we make parameter studies by changing some flow parameters, such as the pitch, helical radius and rotational speed of the spring and the Reynolds number (or fluid viscosity), expected to affect the thrust force experienced by the rotating spring. Results show that the propulsion characteristics depend strongly on the parameters mentioned above. It is observed that the forward thrust increases in a linear fashion with either of the rotational speed or the fluid viscosity. In addition, the thrust is directly proportional to square of the helical radius and but the thrust force is increased and then decreased based on the peak value to the pitch**.** Finally, we also present the appropriate flow and pressure fields visualized to support the observations.

Keywords**—**Fluid viscosity, hydrodynamics, similitude, propulsive force.

I. INTRODUCTION

THE propulsion of a bacterial flagellum in a viscous fluid has attracted many interests in the field of biological hydrodynamics, but remains yet fully understood and thus still a challenging problem. In this study, therefore, we have numerically investigated the flow around a steadily rotating micro-sized spring to further understand such bacterial flagellum propulsion. Note that a bacterium gains thrust (propulsive force) by rotating the flagellum connected to the body through a bio motor to move forward. Many prokaryotic bacteria like *Escherichia coli* during chemotaxis, swim towards or away from certain chemicals using their flagella [1]. It has been proved experimentally that it is flagellar rotation that causes swimming motion [2] For the investigation, we convert the spring model from the micro scale to the macro scale using a similitude law (scale law) and perform simulations on the converted macro-scale model using a commercial software package, CFX v13 (ANSYS).

In this study, it is helpful for us to understand thrust or propulsive force of bacteria having flagellar and the study help us to gain knowledge on hydrodynamic phenomena of swimming motion in the laminar region as well.

II. MATHEMATICAL MODELING

A. Numerical Analysis Model and Method

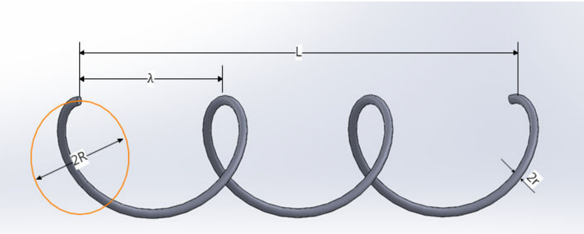

Fig. 1 Numerical model

In this study, performed analysis model such as a spring-like shape (Fig. 1) was used and similitude is applied for better visualization of flows. The spring that L is length, pitch is λ, spring radius is r and helical radius is R is analyzed [3].

First, velocity field and pressure field are observed using the spring with L=200mm, λ=66mm, R=12.7mm, r=1mm. The propulsive force is calculated by changing each helical radius (R) and pitch (λ) to find out the correlation between geometric variation and the force, and similarly, the same model is also calculated with changing viscosity of fluid and rotational speed.

The Reynold's number is given by [4]

$$R_e = \frac{\omega \lambda^2 \rho}{\mu} \tag{1}$$

where ω is rotational speed, λ is pitch, ρ is density and μ is viscosity.

The Reynold's number is kept between 10^{-3} and 10^{-5}. And the governing equation is below [5]

$$\nabla \cdot \vec{U} = 0 \tag{2}$$

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$$\rho_f \frac{d\vec{u}}{dt} + \rho_f(\vec{u} \cdot \nabla)\vec{u} = -\nabla p + \mu_f \nabla^2 \vec{u} \tag{3}$$

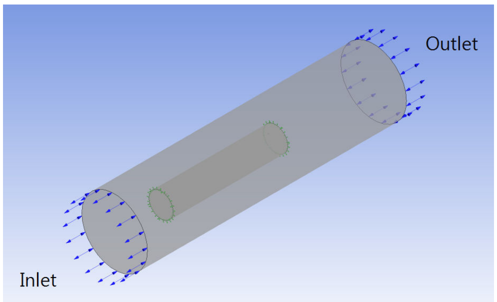


Fig. 2 First method (inner cylinder rotation)

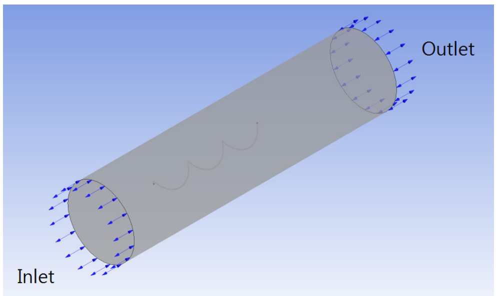


Fig. 3 Second method (outer cylinder rotaion)

There are two methods. One is inner cylinder rotation that means the inner cylinder-shaped domain is rotated and outer cylinder-shaped domain is stationary and then solution is calculated in terms of absolute coordinate system (Fig. 2).

The other is outer cylinder rotation that the inner cylinder-shaped is not present and only one cylinder-shaped domain is rotated, and then solution is calculated in terms of relative coordinate system (Fig. 3).

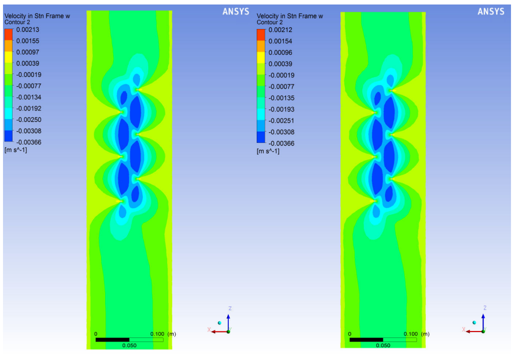
B. Analysis Grid and Condition

In this study, owing to the curvature of the spring, tetrahedral grid was used. Inlet and outlet were applied with both opening condition and pressure condition, and the outer cylinder and inner cylinder were given a no-slip condition, additionally the inner cylinder was given rotating speed. Steady-state analysis of laminar model was performed for numerical convergence and improved accuracy.

III. RESULT

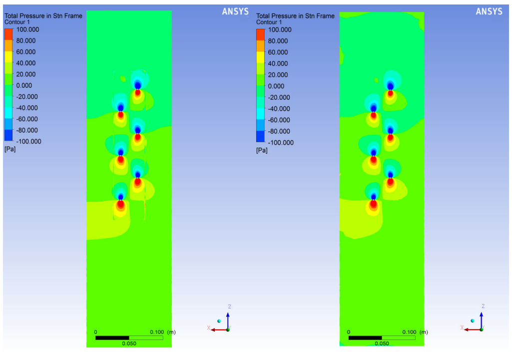
A. Validation

Similar results were obtained in the velocity field and the pressure field around the spring between rotation of the inner cylinder and the outer cylinder. Thus, rotation of the inner cylinder is used in this paper.



(a) (b)

Fig. 4 Comparison between rotation of the inner cylinder (a) and rotation of the outer cylinder (b) in velocity field



(a) (b)

Fig. 5 Comparison between rotation of the inner cylinder (a) and rotation of the outer cylinder (b) in pressure field

B. Analysis Result

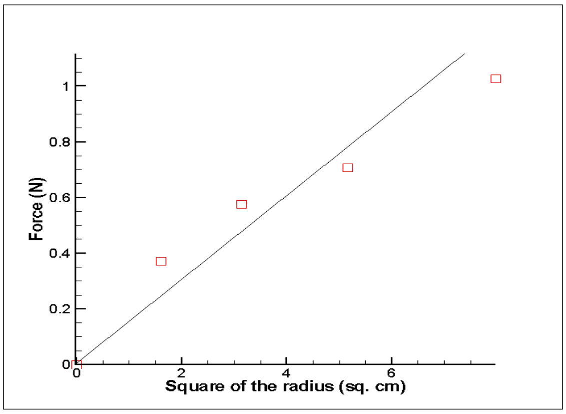


Fig. 6 Effect of the square of the radius on thrust force (propulsive force)

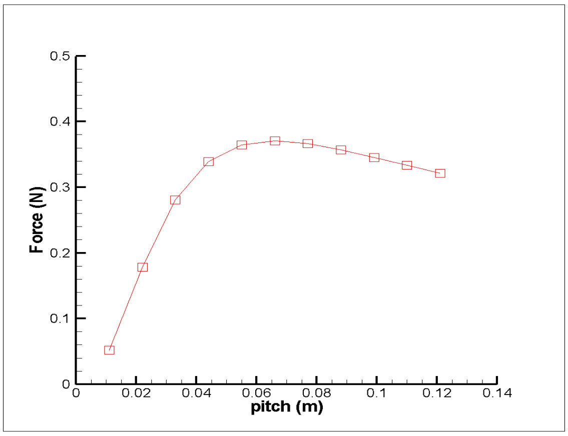


Fig. 7 Effect of pitch on thrust force (propulsive force)

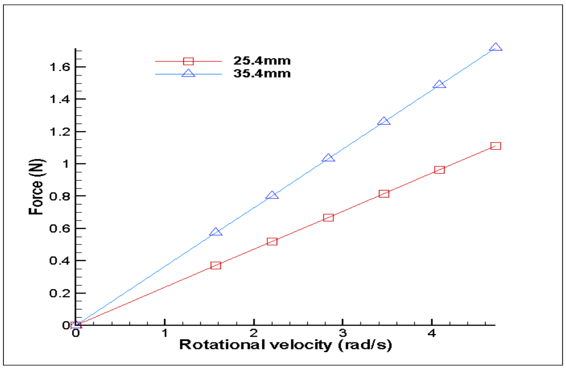


Fig. 8 Effect of rotational speed on thrust force (propulsive force)

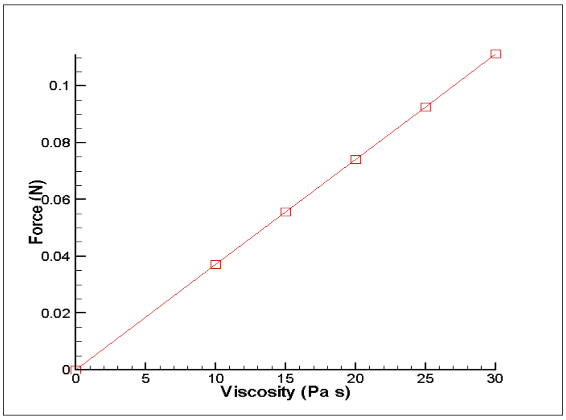


Fig. 9 Effect of the viscosity on thrust force (propulsive force)

Fig. 6 shows variation of radius of helix on propulsive force. The square of helical radius increases, the propulsive force increases.

Fig. 7 shows effect of pitch on thrust force. Initially the force rapidly increases and then after at point of λ=66mm, force slightly decreases rather than before λ=66mm. and there is a maximum point in graph.

Rotational speed of spring is faster, the force linearly increases (Fig. 8).

Finally, the force linearly increases with increasing viscosity of fluid (Fig. 9).

IV. CONCLUSION

The study for parameters was conducted by numerical analysis on fluid flow around spring in laminar flow.

The propulsion characteristics depend strongly on the parameters mentioned above. It is observed that the forward thrust increases in a linear fashion with either of the rotational speed or the fluid viscosity. In addition, the thrust is directly proportional to square of the helical radius but the thrust force is increased and then decreased based on the peak value to the pitch, and maximum value of force is found.

Finally, we also present the appropriate flow and pressure fields visualized to support the observation**s.**

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