Swimming by reciprocal motion at low Reynolds number

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INTRODUCTION

In fluid mechanics, Reynolds number (**Re**) is the ratio of a fluid inertia force to a viscous force. In general, an object cannot move forward by reciprocal motion at low Reynolds number. However, it needs to be met under certain conditions, so in fact, in some liquids, an object is still possible to move forward by reciprocal motion at low Reynolds number. In this experiment, we will discuss whether an object in different liquids can swim by reciprocal motion or by non-reciprocal motion.

THEOREM

The scallop theorem

At low Reynolds number in Newtonian fluids, the viscous force dominates. If a swimmer is in reciprocal motion, it will never achieve propulsion. The equation describing the motion of an incompressible Newtonian fluid is Navier-Stokes equation which is linear and independent of time.

$$\rho\frac{\partial u}{\partial t} + \rho(\vec{u}\cdot\nabla)\vec{u} = -\nabla P + \mu\nabla^2\vec{u} + F$$

The scallop theorem is broken

At low Reynolds number propulsion of a scallop is possible in shear thickening and shear thinning fluids. Differences in the opening and closing rates give rise to differences in the corresponding shear rates and hence the viscosities of the non-Newtonian fluid will change with different rates.

$$\tau = \mu\frac{\partial u}{\partial y}$$

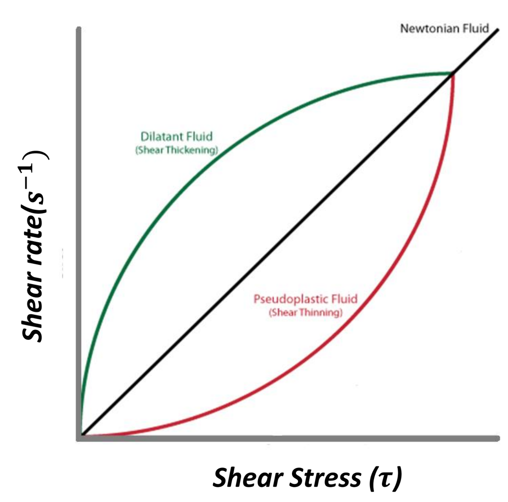

Fig. 1

SETUP

The robot is controlled by Bluetooth.

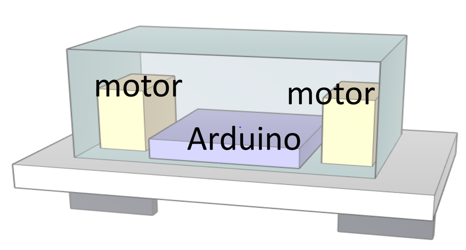

Fig. 2

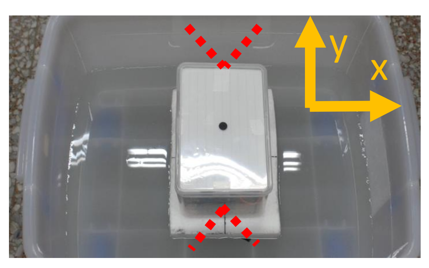

Fig. 3

METHOD

1. We put the robot in the water (high Re Newtonian fluid), the glycerin (low Re Newtonian fluid) and the corn flour water (low Re non-Newtonian fluid), observing if the robot can swim in reciprocal or non-reciprocal motion.
2. We do an image analysis to track the position of the robot in the liquid over time.
3. Motion mode :
   - Reciprocal motion :

Mode 1

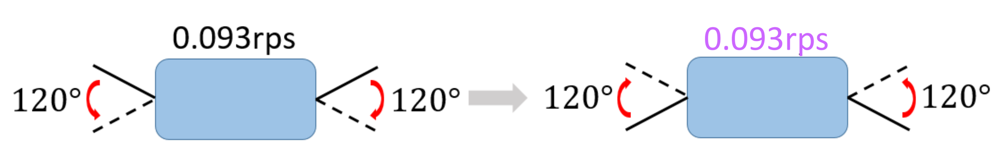

Fig. 4

Mode 2

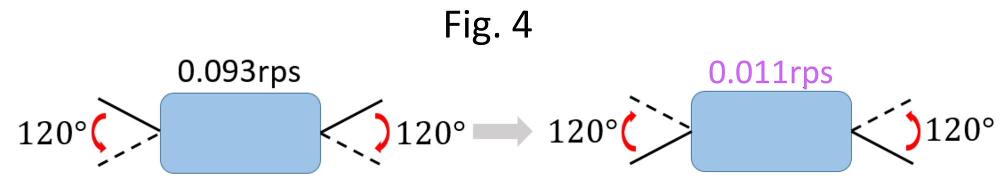

Fig. 5

- Non-reciprocal motion :

Mode 3 (0.093rps)

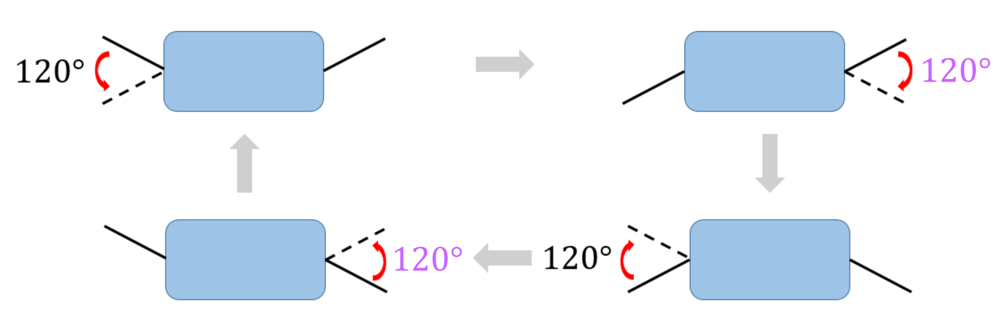

Fig. 6

Mode 4 (0.093rps)

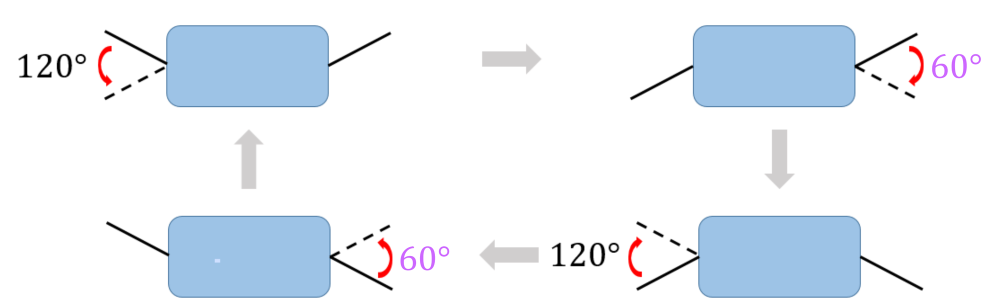

Fig. 7

RESULT – RECIPROCAL MOTION

- Water :

$$Re = \frac{\rho v D}{\mu} \cong 63.25$$

$Re > 1$, which means that the influence of the inertia force is greater than the viscous force. Therefore, when the robot swims in the water, it is mainly affected by inertial forces.

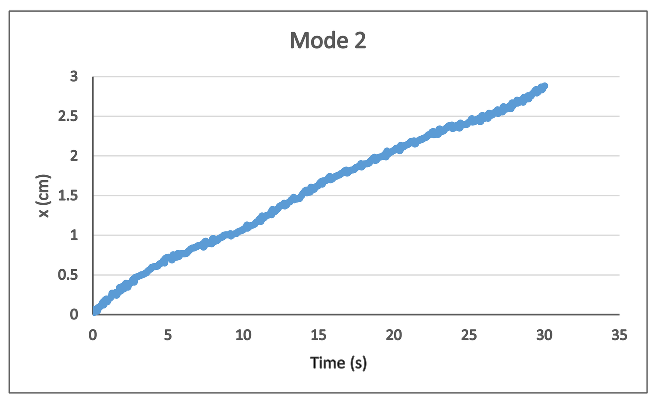

Fig. 8

- Glycerin :

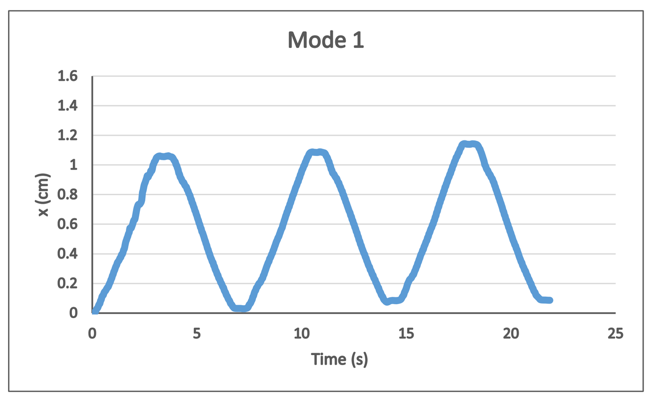

Fig. 9

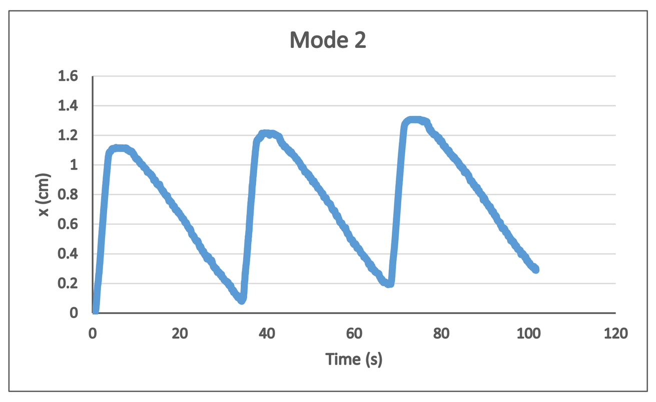

Fig. 10

- Corn flour water :

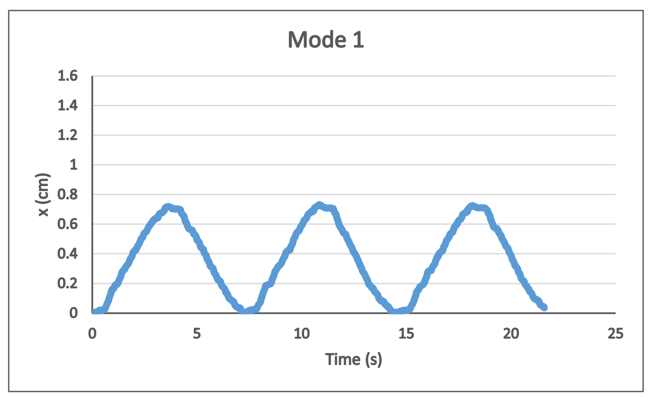

Fig. 11

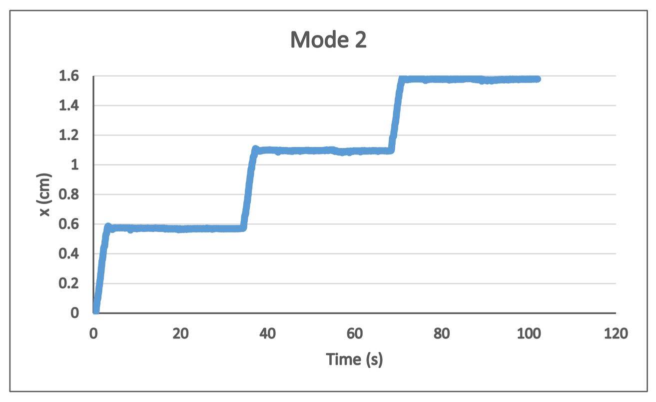

Fig. 12

RESULT – NON-RECIPROCAL MOTION

- Glycerin :

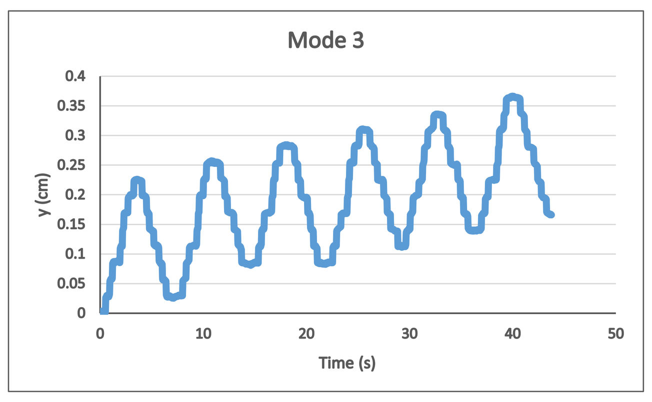

Fig. 13

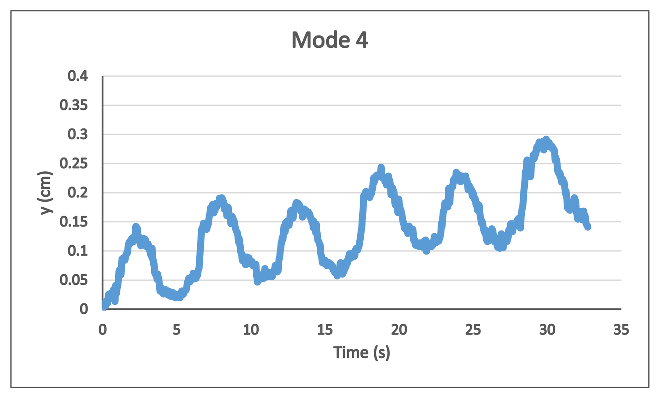

Fig. 14

- Corn flour water :

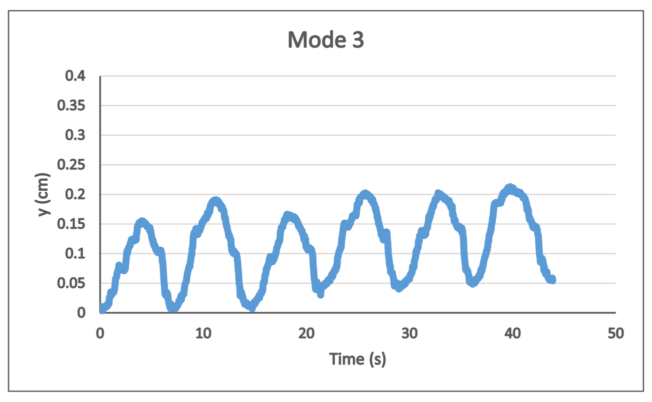

Fig. 15

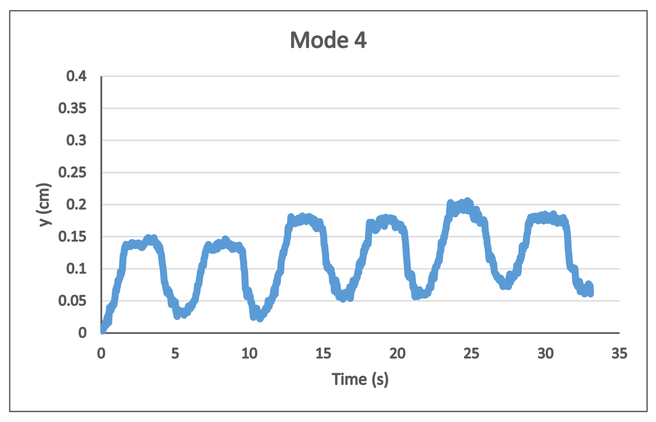

Fig. 16

CONCLUSION

1. The scallop theorem only works at low Reynolds number in the Newtonian fluid. In the non-Newtonian fluid, even though the object just moves in the reciprocal motion, it can still swim.
2. Non-reciprocal motion our set is an inefficient way to swim at low Reynolds number, no mater in what kinds of fluid. Therefore, the angles of the motion do not have much influence.

REFERENCE

1. Purcell, E. M. Life at low Reynolds-number. Am. J. Phys. 45, 3–11 (1977).
2. Qiu, T., T. C. Lee, A. G. Mark, K. I. Morozov, R. Münster, O. Mierka, S. Turek, A. M. Leshansky, and P. Fischer, 2014, “Swimming by reciprocal motion at low Reynolds number,” Nat. Commun. 5, 5119.