Hydrodynamic synchronization of flagella pair

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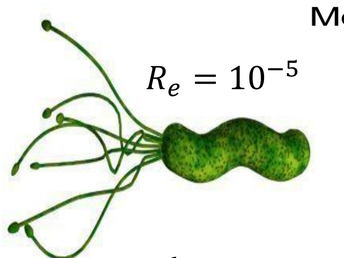
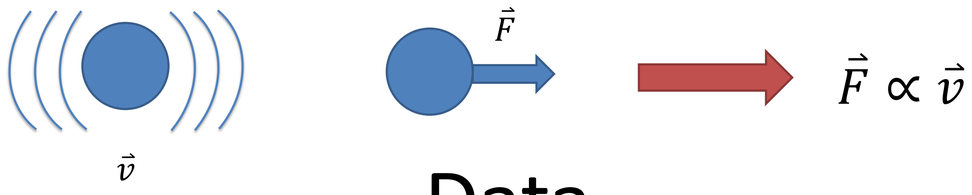
Motivation

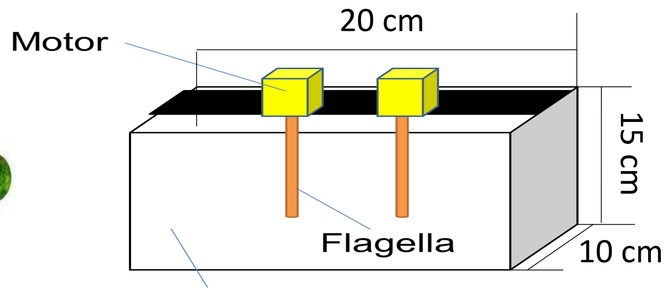
- The E coli. can move fast with flagella.
- The biological interaction between each flagella is to slow.
- How the flagella influence each other without biologically?

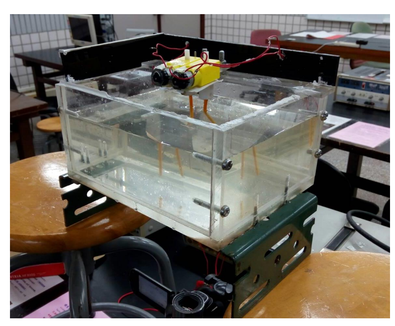


- $Re = \frac{\rho v l}{\mu}$. Flagella : $\rho \cong 1\, g/cm^3, v \cong 10^{-6}\, {}^{m}/_{s}, l \cong 10^{-6} m, \mu \cong 0.001 Pa \cdot s$



Setup



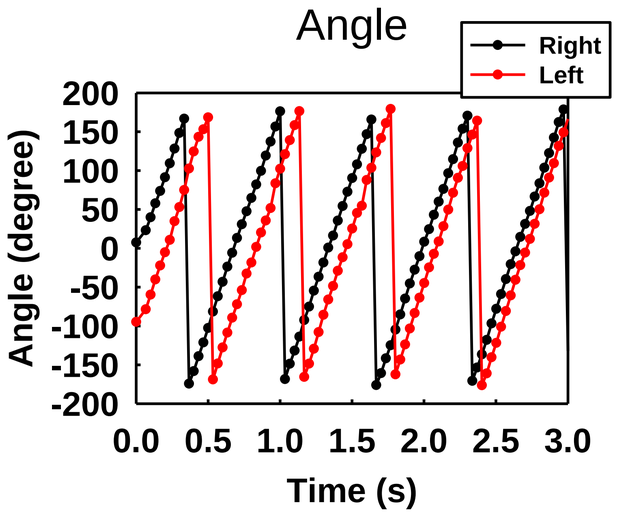


$R_e \cong 10^{-5}$

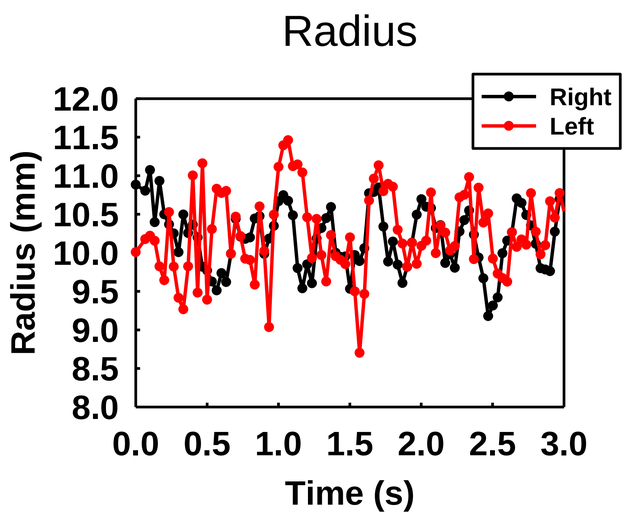
The length of the flagella is 10cm, the velocity is about $6.28 * 10^{-2}\, {}^{m}/_{s}$, and the density is about $1.2 {}^{g}/_{cm^3}$, so as the glycerin. The viscosity of the glycerin is 1.412 Pa·s (water is 0.001)
The angular velocity and the distance between two flagella is controllable.
The video is taken from the bottom side of the chamber.

Data

Initial State | In-phase | Out of phase



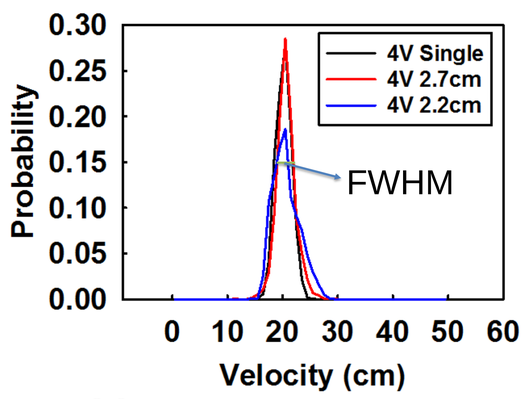
Angle of flagella

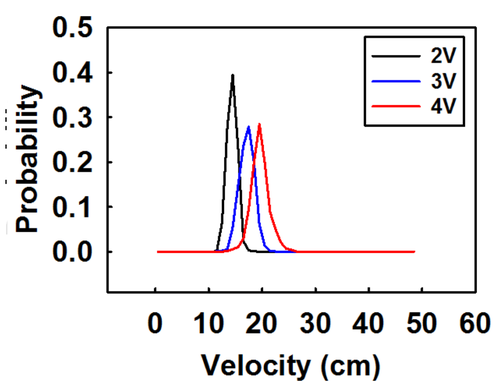


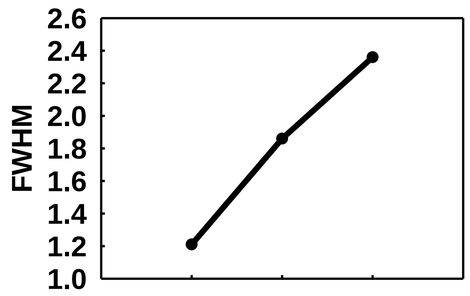
Radius of flagella

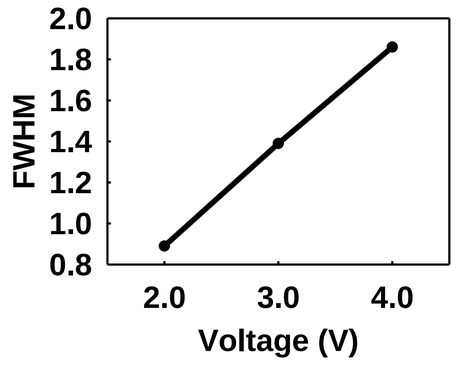
How to work

Take video → Track → Analyze



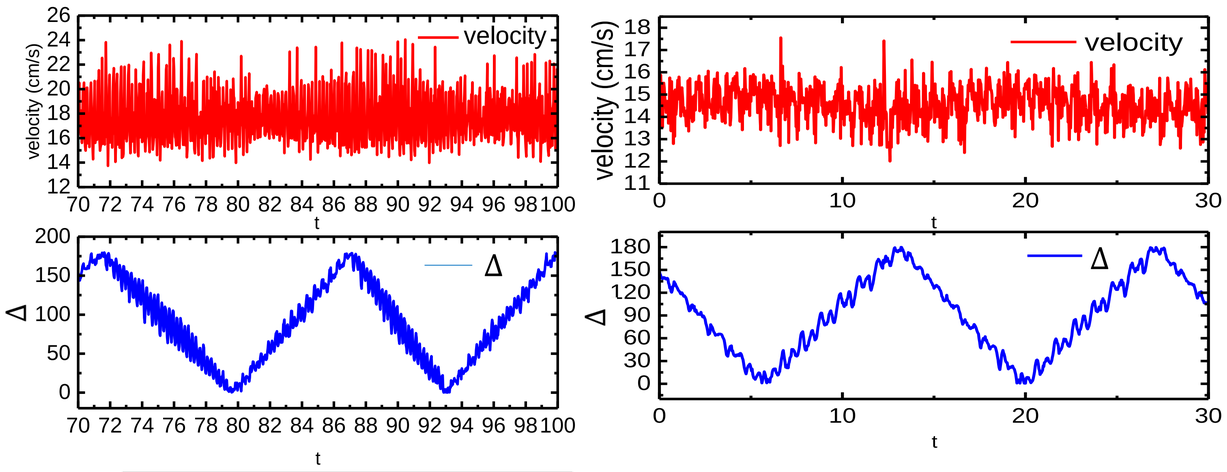


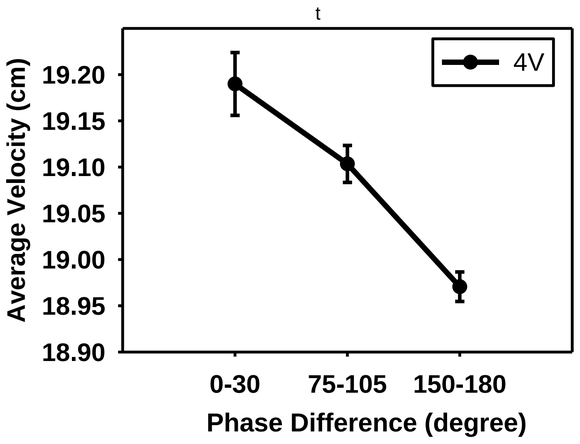




- If distance is far, the motion is similar to the motion with only one flagella.
- We can see the only one flagella with infinite distance.
- The velocity also influence the distribution of velocity.
- The bigger the value of the voltage is, the bigger the interval of the difference of velocity.
- There are many Gaussian distribution in small distance

Analysis

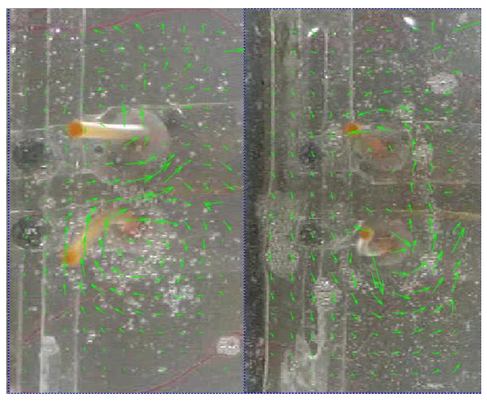




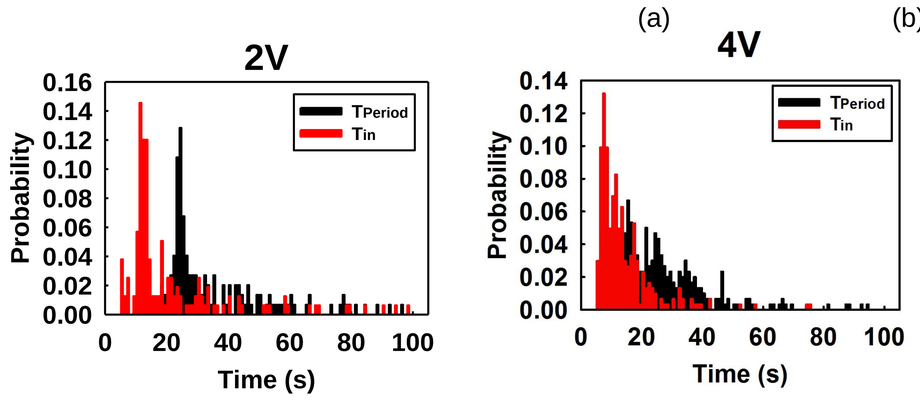
- Phase Difference →Velocity
- In low Reynold number environment,
  $\vec{F} \propto \vec{v}$
- Therefore, we can find that the force is related to the phase difference.

The figure show the observation that the phase difference get bigger, the velocity become smaller.

- PIV→Flow field→Force
- Out of phase → Flow blocks the motion of flagella
- In-phase → Flow puts the motion of flagella



(a) (b)



- The time from in-phase to in-phase is short.
- Weak force may make the time of out phase become longer.
- Both of above observation show that the phase lock is not stable when the force is weak.

Conclusion

- The motion of flagella pair in low Reynolds number environment is like couple oscillation. θ in here is similar to x in couple oscillation.
- In the motion, the glycerin is similar to the spring in couple oscillation.
- The phase difference may influence force between two flagella.
- The phase difference influence the force between two flagella, and can be realize from velocity.
- The result of experiment can show us that the mode of the motion of flagella is not related to the bacteria itself.

Reference

1.Raymond E. Goldstein, M. Polin, and I. Tuval. Phys. Rev. Lett. 103, 168103 (2009)