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Fluid Machinery of Bio Locomotion of an Insect

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Introduction

- The realm of the low-Reynolds number encompasses the world of the very small, the very viscous, or the very slow.

- While engineers have long taken advantage of these lubrication forces in the design of bearings, we sought to prove that similarly forces could be used for propulsion. To the best of our knowledge, until Robosnail 1, there has been no prior experimentation.

- We are extremely good at designing things that can move on flat surfaces e.g we can build a road and then design a vehicle to move on it. By looking at these natural systems we can actually build machines that can climb a vertical wall.So we can learn a lot from these natural systems.

Locomotion

- The movement of an organism from one place to another, often by the action of appendages such as flagella, limbs, or wings.

- The research in snail locomotion has inspired a branch of low-Reynolds number loco- motion based on peristaltic waves. It has been known that motions of boundaries over thin layers of viscous fluid can generate very large shear and normal stresses in the low - Re lubrication regime.

Peristalsis: A wave like series of muscular contractions

Locomotion at Low Reynolds Number

All of the systems described here operate at extremely low Reynolds number, the regime
where viscous forces dominate over all inertial and buoyant forces. In this limit, the NavierStokes
equations reduce to the Stokes equations. The Navier-Stokes equations for incompressible
Newtonian fluids,

$$\rho(\frac{\partial v}{\partial t} + v \cdot \nabla v) = -\nabla p + \mu \nabla^2 v + f$$

where ρ is the fluid density, v is the velocity field, p is the pressure, μ is the fluid viscosity,
and f is an applied body force on the fluid.

The Reynolds number describes the relative magnitudes of inertial and viscous forces:

$$Re = \frac{\rho V L}{\mu}$$

Where V and L are characteristic velocities and lengths in the flow. In the absence of body
forces, at the limit of low Reynolds number (usually when V or L, the right-hand terms
Navier-Stokes equation become zero and f = 0, resulting in the Stokes equation:

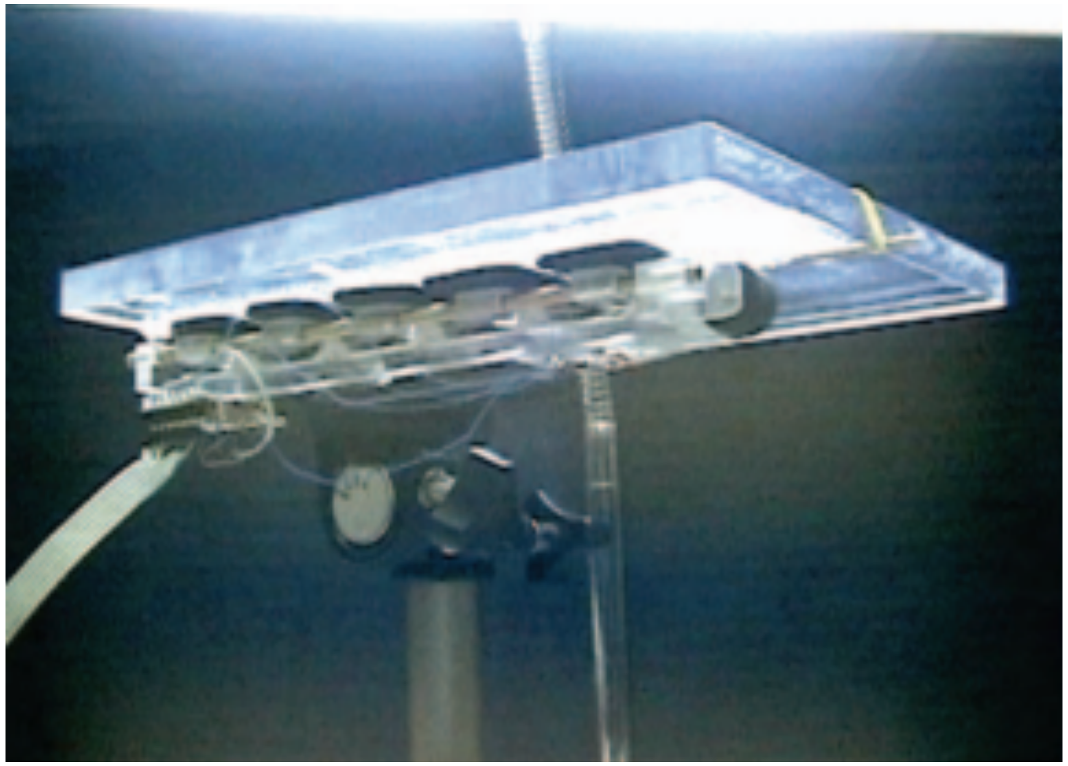
$$\nabla \cdot v = 0$$

$$\nabla p = \mu \nabla^2 v$$

Two types of Mechanical Snail

- Robosnail 1 utilises lubrication pressures generated in a Newtonian fluid under a steadily undulating foot to propel itself forward. Tractoring force and velocity measurements are in agreement with analytic and numerical solutions.

- Robosnail 2, modelled after real land snails, uses in-plane compressions of a flat foot on a mucus substitute such as Laponite or Carbopol. Robosnail 2 exploits the non-Newtonian qualities (yield-stress, shear thinning) of the fluid solution to locomote.



Two types of Mechanical Snail

Robosnail 1

- Which uses a waving foot to move over viscous newtonian fluids.
- As in the case of Robosnail 1, it uses peristalsis and lubrication pressures.

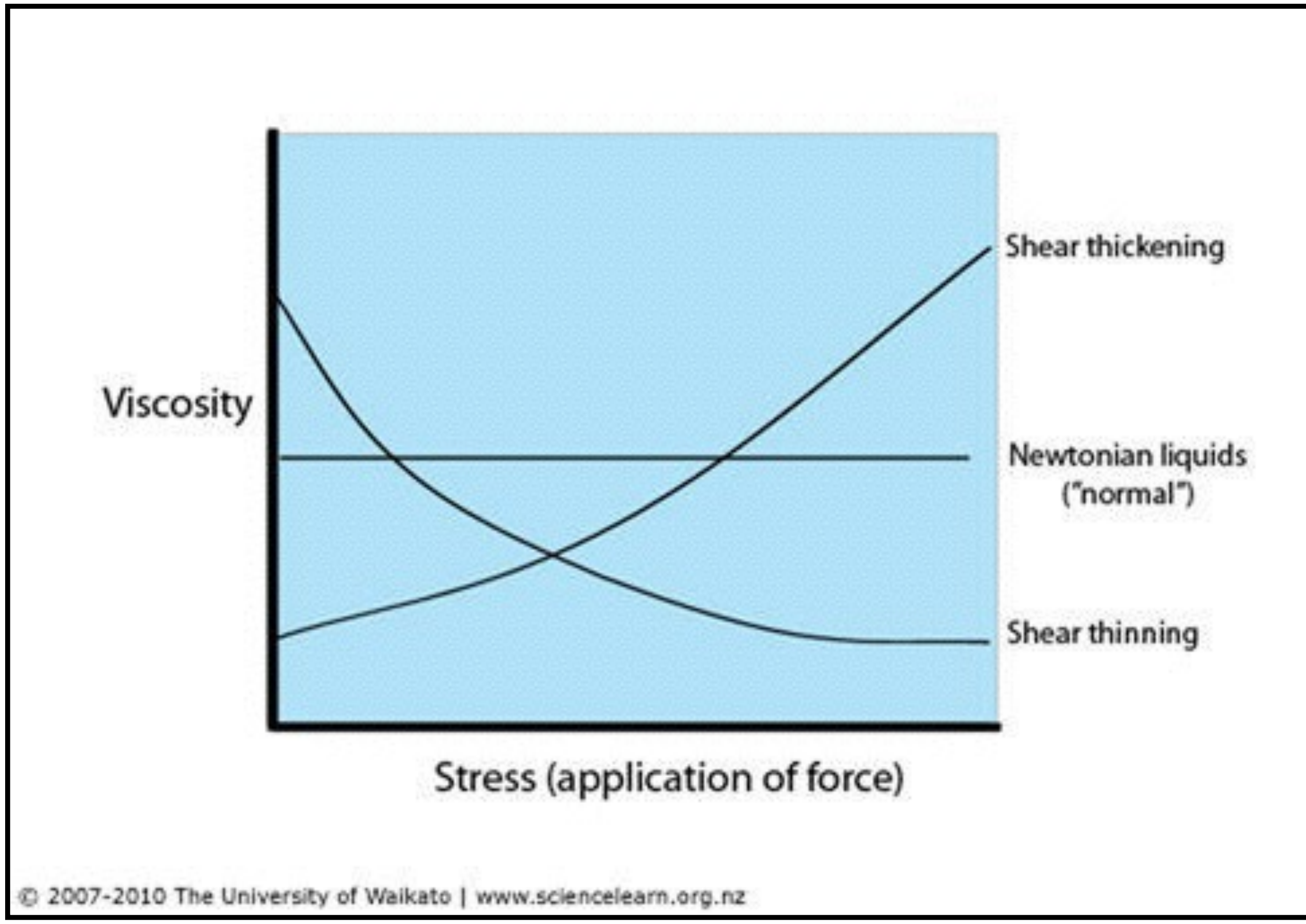
Robosnail 2

- That uses a sliding foot to move over a shear-thinning fluid.
- Robosnail 2 is the closest to the functioning of real snails, using adhesion and sliding .
- While Robosnail 2 is constrained by the limitation that it requires non-newtonian fluid to operate, it is capable of such feats as moving up walls or in an inverted position.

Peristalsis: A wave like series of muscular contractions

Shear-Thinning Fluids

- Newtonian fluids have a constant viscosity and therefore a linear response to in- creasing strain rate.
- Non-newtonian fluids have variable viscosity and a non-linear response.
- a shear-thinning fluid is one which has a viscosity that decreases with increasing shear rate.
- Two secondary properties that affect snail locomotion are the **finite yield stress** and the **restructuring time**.
- Carbopol and snail mucus, for our purposes, can be classified as types of finite yield stress fluid, which is one particular type of shear-thinning fluid.



THEORY and NUMERICAL SIMULATIONS:

- The theory and numerical simulations reveal the various characteristic forces and velocities that can be attained by changing the waving profile.

Underlying Physics of Robosnail 1

$$\tau = \mu \frac{du}{dy}$$ [NS/m^2]

- μ= Viscosity
- τ= Shear Stress
- Valid only for a family of fluids called **Newtonian Fluids**

$$\frac{\partial p}{\partial x} = \frac{\mu \partial^2 u}{\partial y^2}$$

- Lubrication Fluid

At this point it becomes useful to non-dimensionalize the equations, rescaling the relevant quantities as follows:

$$\hat{h} = f(\hat{x} - \hat{V}_w t)$$

For simplification of analysis, we assume that the waving membrane is periodic with a wavelength such that

↓

$$\hat{h}(x,t) = \hat{h}(\hat{x} + n\lambda, t)$$

$$\hat{x} = \lambda x$$

$$\hat{z} = \hat{H} z$$

$$\hat{u} = \hat{V}_w u$$

$$\hat{p} = \frac{\lambda \mu \hat{V}_w}{\hat{H}^2} p$$

$$\hat{h} = \hat{H} h$$

$$\hat{V}_s = \hat{V}_w V_s$$

$$\hat{F}_t = \frac{\lambda^2 \mu \hat{V}_w}{\hat{H}^2} f_t$$

Vˆw :Speed of the Wave

hˆ(x,t): The changing shape of the snail foot is described by the fluid thickness height

Hˆ = av(hˆ) :Average Height

Vs:Resultant Velocity of the Snail

Fˆt: Tractoring Force

aˆ = Hˆ min(hˆ) :Amplitude

The lubrication equation becomes in dimensionless form.

$$\frac{\partial^2 \hat{u}}{\partial z^2} = \frac{\partial p}{\partial x}$$

For thin profiles, pressure does not vary across the depth of the film. Hence, for any given x-position, the pressure is constant. The flow profile then must be parabolic for any given x-position, taking the form

$$\frac{du}{dz} = \frac{\partial p}{\partial x} z + C_1$$

$$u(z) = \frac{\partial p}{\partial x} z^2 + C_1 z + C_2 \qquad (1)$$

The integration constants **C_1** and **C_2** are determined by boundary conditions at the foot and the substrate.

To solve for these constants we switch to a reference frame traveling with the wave!

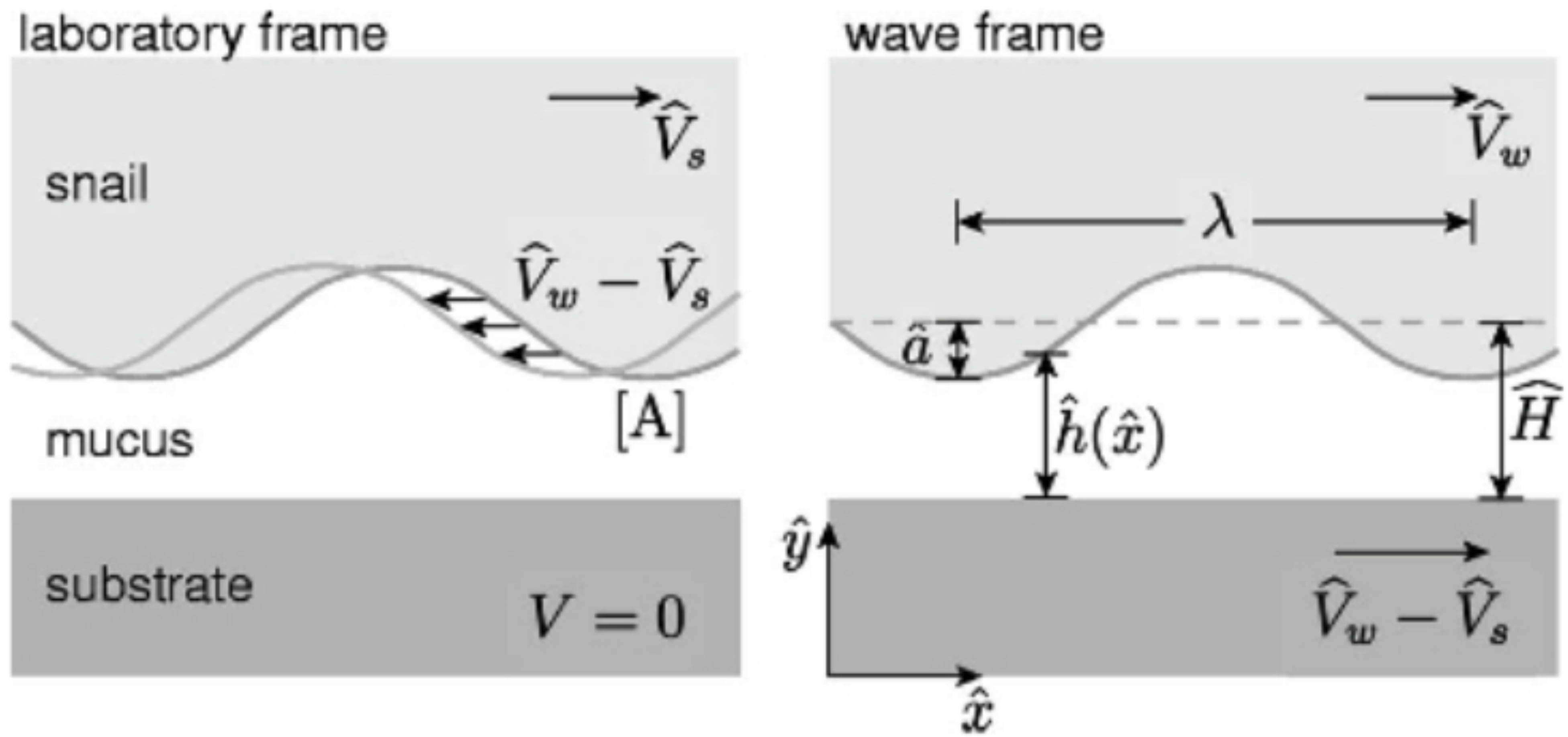
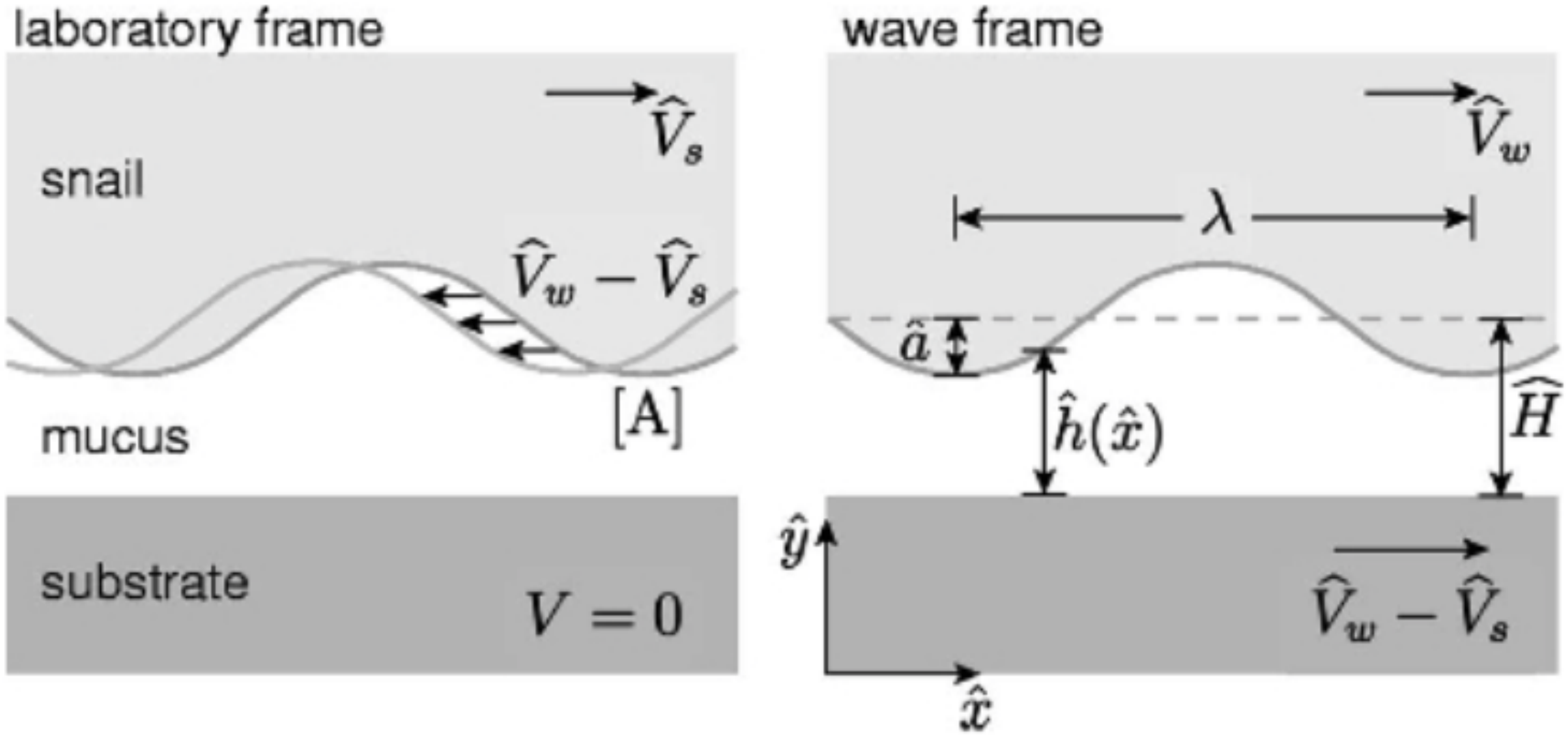


Fig:Switching to a useful reference frame for solving the flow underneath a self- propelled, peristaltic waving membrane. In the laboratory frame, the foot height is a function of x and t . In the wave frame (a frame of reference following the wave crests) the height is only dependent on x and the flow can be modeled as steady.



Flow is steady

The volume flow rate **Q = udz** (per unit width) is a constant

Velocities in New reference frame

$$\hat{V}|_{z=0} = \hat{V}_w - \hat{V}_s$$

$$\hat{V}|_{z=h} = \hat{V}_w$$

or in dimensionless terms

$$u|_{z=0} = 1 - V_s$$

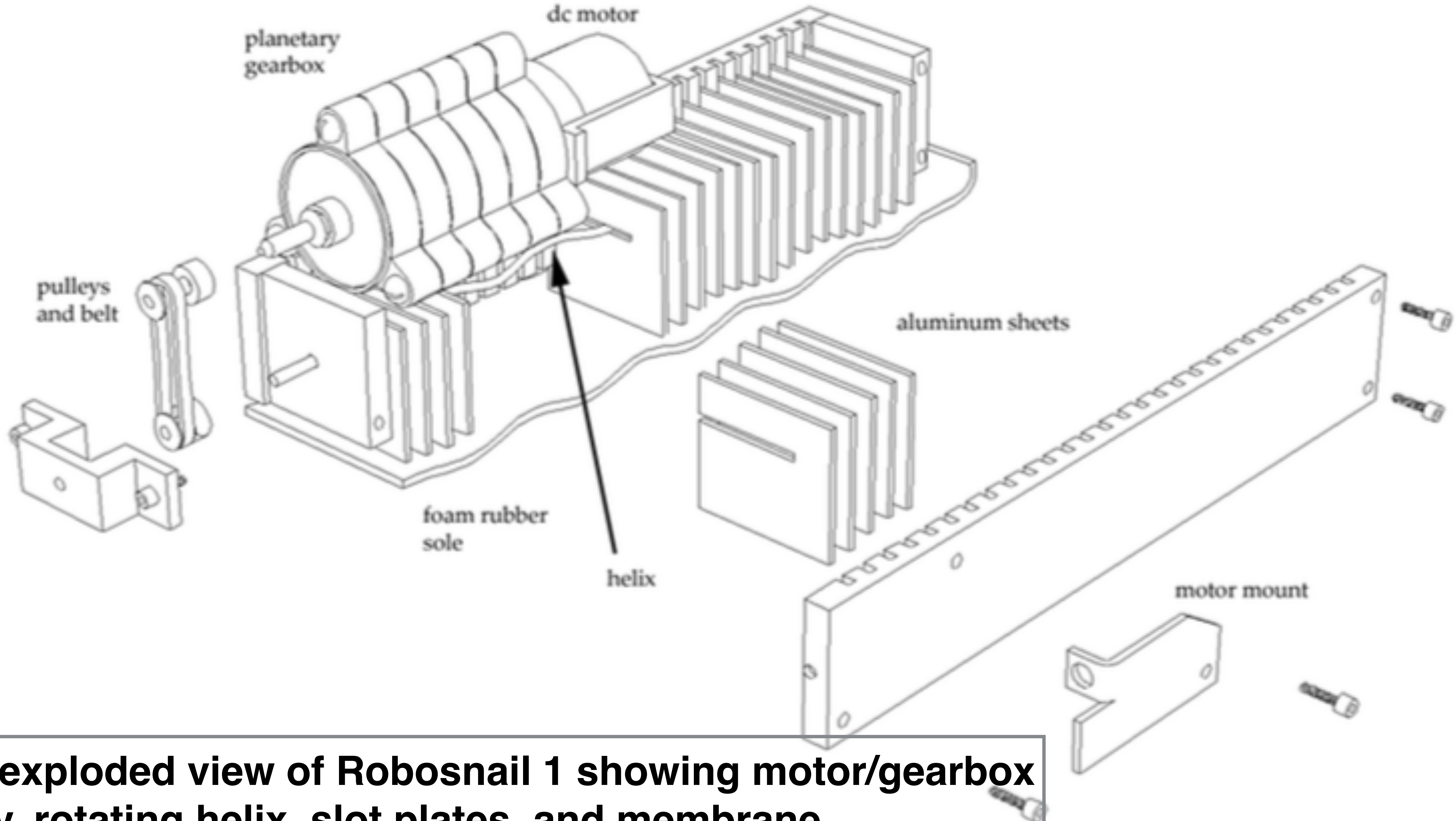
$$u|_{z=1} = 1$$

Applying these boundary conditions to equation (1)

The Velocity profile becomes:

$$u(z) = \frac{1}{2}\frac{\partial p}{\partial x} z(z-h) + V_s\left(\frac{z}{h} - 1\right) + 1$$

Mechanism



Partially exploded view of Robosnail 1 showing motor/gearbox assembly, rotating helix, slot plates, and membrane.

1. The most basic wave that can be generated with the waving foot is a sinusoidal wave.
2. To do this, we used a shallow helix threaded through slotted plates which are constrained to move vertically.
3. The bottom edges of the rectangular plates are axed to a flexible membrane.
4. Each of the plates then acts as a connecting rod, with its section of helix acting as a crank, transferring the vertical component of its rotational motion to its part of the membrane.
5. The helix, thus acting as a crank, was driven by a heavily geared-down motor.
6. The resultant motion of the rotating helical crank is a traveling sinusoid along the length of the membrane.
7. The wave speed is simply equal to the wavelengths divided by the rotations per second.

Conclusions

- Research on robosnail 1 has shown that peristaltic waves of a mem- brane can generate significant propulsive forces when lubricated with a newtonian fluid and brought close to a solid substrate.
- The theory and numerical simulations reveal the various characteristic forces and velocities that can be attained by changing the waving profile, and experimental results confirm the results for the basic, sinusoidal wave shape.

Reference

- Assistant Professor Annette "Peko" Hosoi and her colleagues in the Mechanical Engineering Department
- BIo-Inspired Fluid Locomotion by Brian Chan(Hatsopoulos Microfluids Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.)
- Purcell. “Life at Low Reynolds Number”. American Journal of Physics, 45:3–11,1977

Thank you for your attention!