Biology 427 Biomechanics
Lecture 27. Accelerating flows

• Recap: low Re flows
• Added mass forces
• Propulsion with a new approach
• Size limits of intertidal organisms

Posters Due Mon Dec 5, 5 pm
https://catalyst.uw.edu/collectit/dropbox/danielt/36940
Ciliary metachrony

Problems:
- boundaries
- density of cilia
- mucus
- and several important regulatory issues

\[ D = \frac{2\pi \mu U \mu l}{\ln \left( \frac{l}{a} \right) - 0.897} \]

\[ D = \frac{4\pi \mu U \mu l}{\ln \left( \frac{l}{a} \right) + 0.193} \]
Steady flow: the velocity at any point in space is constant

Unsteady flow: the velocity at any point in space changes

Example of steady flow?  
Example of unsteady flow?

Why would unsteady flow be more than just a drag?
bubble $V = 1 \text{ mm}^3 = 1 \times 10^{-9} \text{ m}^3$
bubble $m = 1.2 \times 10^{-9} \text{ kg}$
$\rho_{\text{water}} = 1000 \text{ kg/m}^3$
$F_b = \rho V g = 9.8 \times 10^{-6} \text{ N}$
$F = m \frac{du}{dt}$ (Newton)
$\frac{du}{dt} = 9800 \text{ m/s} = 1000 \times \text{ gravity.}$
\[ F = m \frac{du}{dt} + \text{"Vol" } \rho \frac{du}{dt} \]
\[ = m \frac{du}{dt} + \alpha \rho V \frac{du}{dt} \]
\[ \alpha : \text{ added-mass coefficient} \]

\[ F = (m + \alpha \rho V) \frac{du}{dt} \]
\[ = m' \frac{du}{dt} \text{ (virtual mass, } m') \]

\[ \frac{(P_2 - P_1)}{\rho} = \frac{(u_1^2 - u_2^2)}{2} \]

No net force?
bubble $V = 1 \text{ mm}^3 = 1 \times 10^{-9} \text{ m}^3$
bubble $m = 1.2 \times 10^{-9} \text{ kg}$
bubble $m' = 1.2 \times 10^{-9} \text{ kg} + \alpha \rho_w V$
bubble $m' = 5 \times 10^{-7} \text{ kg}$
$\rho_{\text{water}} = 1000 \text{ kg/m}^3$
$F_b = \rho V g = 9.8 \times 10^{-6} \text{ N}$
$F = m \frac{du}{dt}$
$\frac{du}{dt} = 20 \text{ m/s} = 2 \times \text{ gravity}$.
The added-mass coefficient depends on the shape of the object.
Balance of forces (thrust and “drag”) for a swimmer!

Thrust = $C_D \rho S u^2/2 + \text{“something else”}$

= $C_D \rho S u^2/2 + \alpha \rho V \frac{du}{dt}$

“Drag” = $C_{D_{\text{body}}} \rho S_{\text{body}} u_{\text{body}}^2/2 + \alpha_{\text{body}} \rho V_{\text{body}} \frac{du_{\text{body}}}{dt}$
Which way does the added-mass force vector point: assume the angular velocity is periodic (sinusoidal).

(a) at the beginning of the power stroke
(b) at the end of the power stroke?
(c) at the beginning of the recovery stroke?
(d) end of the recovery stroke?
Lateral force per unit length

Lighthill’s slender body theory:

Thrust = \( m'(V^2/2 - V \frac{dh}{dt}) \)

Anguilliform swimming
You don’t have to swim to feel accelerations!

Denny, Daniel, Koehl
Strength -- a material property: the **stress** at which something fails. The force to dislodge (tenacity):

\[ F_{\text{Dislodge}} = \sigma_{\text{max}} A \]

Drag -- a fluid **force** parallel to flow

\[ F_{\text{Drag}} = \frac{1}{2} \rho S C_D U^2 \]

Added-mass -- a fluid **force** parallel to flow

If drag is the only force:
how does the ratio of fluid force to tenacity scale with body size?

\[ F_{\text{Added-mass}} = \alpha \rho V \frac{dU}{dt} \]

If drag + added mass:
how does the ratio of fluid force to tenacity scale with body size?
Virtual buoyancy: which way will a helium balloon move?
Which way does the added-mass force vector point: assume the angular velocity is periodic (sinusoidal).
(a) at the beginning of the power stroke
(b) at the end of the power stroke?
(c) at the beginning of the recovery stroke?
(d) end of the recovery stroke?

\[ F_{\text{Added-mass}} = \alpha \rho V \frac{dU}{dt} \]
\[ F_{\text{Drag}} = \frac{1}{2} \rho S C_D U^2 \]
\[ F_{\text{Dislodge}} = \sigma_{\text{max}} A \]

If drag is the only force: how does the ratio of fluid force to tenacity scale with body size?

If drag + added mass: how does the ratio of fluid force to tenacity scale with body size?