Interfaces — Rayleigh-Taylor 1.

Physics 216/116

Lecture V — Instabilities I

So far: — basic eqns.
— Potential Flow
— Low Re flow

S + Sphere + potential flow

↔ General ideas wake

St + Stokesian flow

↓ coming

P + Blasius Boundary Layer (Laminar)

↓

← wakes, drag, lift

Turbulent wakes, Turbulence

all: { energy source for flow is body motion ($\underline{U}$) }

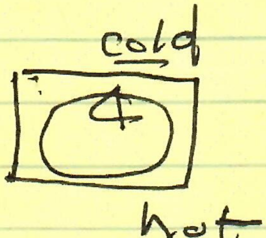
so: Instability → { continuation → KH ; diversion → RT, RB }

[stored free energy → fluid motions → chaos, turbulence dissipation.]

⇒ Relaxation — initial stage usually is linear instability

① — stored free energy {equilibrium + small pert → growth}

i.e.

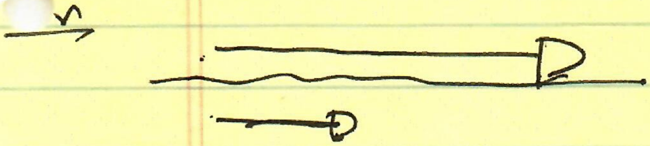


⇒ rises hot air

Rayleigh-Benard convection

→ ∇T ⟺ thermal buoyancy energy

②

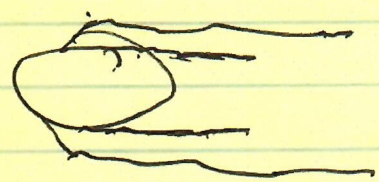


Kelvin-Helmholtz shear flow

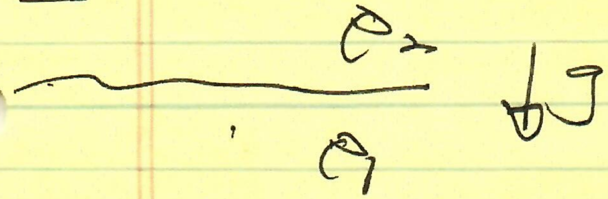
→ ∇V ⟺ kinetic energy flow shear

relevant to breakdown of wake (after separation)

⇒ onset of turbulent wake



③ or



Rayleigh-Taylor

→ $\nabla\rho + g$ (buoyancy)

but, heat not central.

→ gravitational potential energy.

Real Story / Question:

Relaxation ⇒ Linear Instability → Nonlinear Evolution saturation

→ Final state

(incl. dissipation)
often turbulent.

Hydro stability is "Yuge" subject

c.f. Chandrasekhar

[Theory of Hydrodynamic and Hydromagnetic stability]

Here: — First step.

— 2 classes →

① interfacial instabilities
→ RT, KH

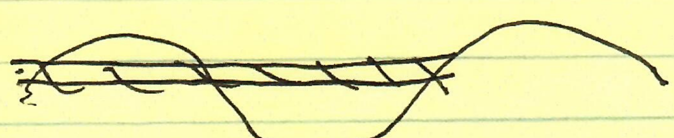
② Convection
→ RB

+ homework

1.) Interfacial Instabilities

if L st $1/L = \frac{1}{\rho}\frac{\partial \rho}{\partial z}, \frac{1}{V}\frac{\partial V}{\partial z}$

$k_x L \ll 1$



⇒ treat gradient as held in an interface/layer.

⇒ strategy: — 2 homogeneous media

⊕

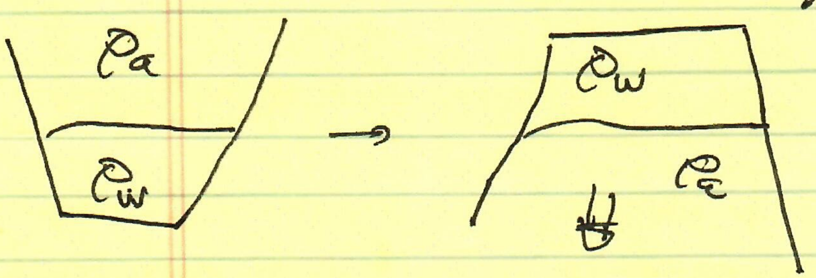
— matching conditions

⇔ significant overlap with theory of {surface phenomena, droplets, etc.

⇒ biophysics:

n.b. in 'Life at low Reynolds number,' surface tension relevant.

⇒ Prime Example 1: Rayleigh–Taylor
(c.f. posted papers, especially Taylor 1950).



why? ⇒
Ripples on surface grow ⇒ R.-T. instability

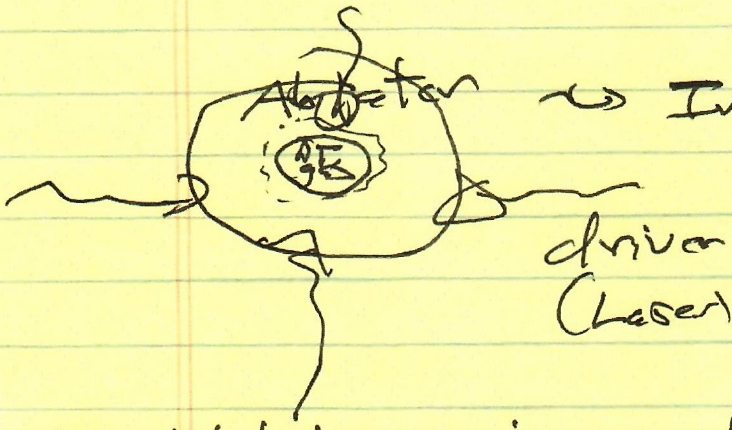
→ invert

nothing happens!

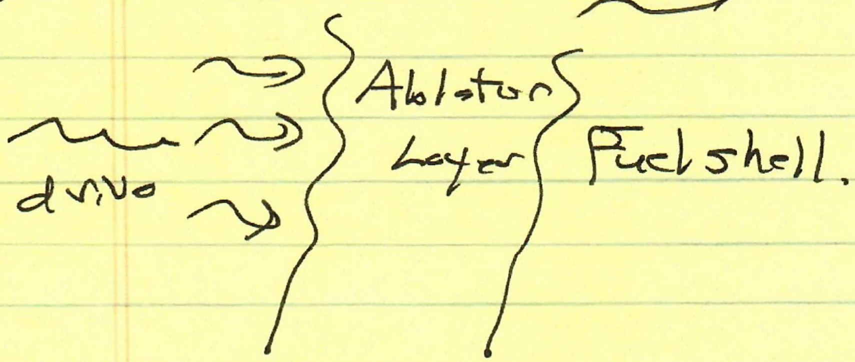
⇒ cardboard effectively takes $\gamma_{surf.} \to \infty$.

ρ_H / ρ_L $\downarrow g$ → contrived ?!

<u>but</u> ICF (controlled and otherwise)

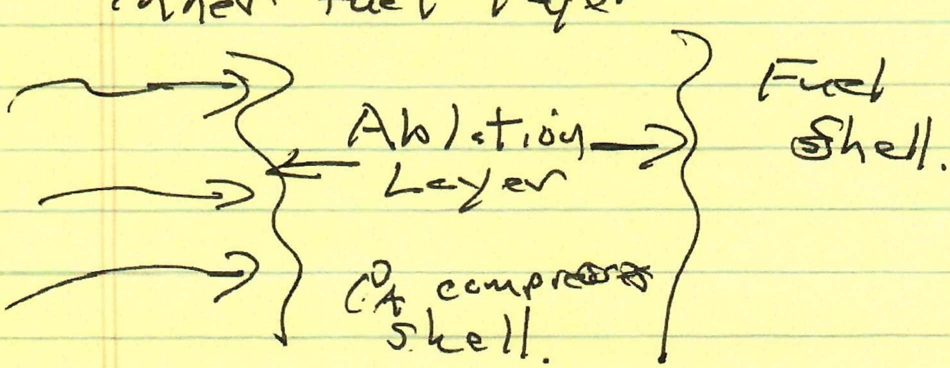


⇒ ablation-driven rocket: <u>driver complexes</u>

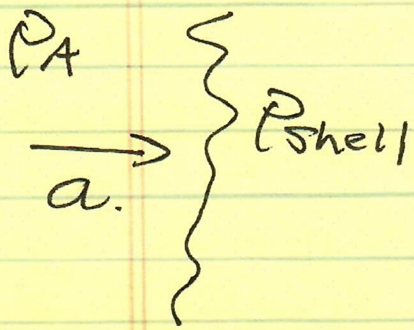


treat: compression dynamics as rocket equation

⇒ drive causes ablator layer to heat and expand, thus compressing inner fuel layer



Consider situation:

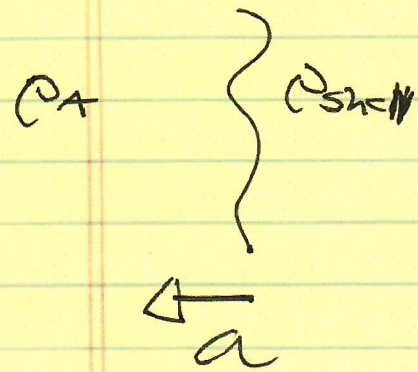


$\rho_{shell} > \rho_a$

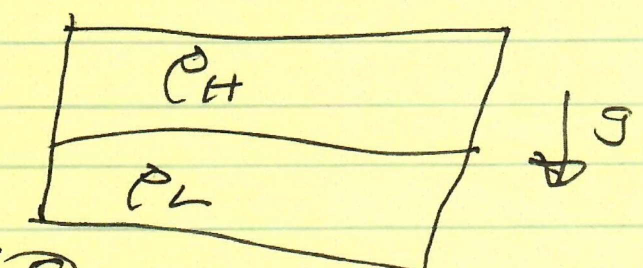
"Light/low density fluid (gas) pushing on (i.e. accelerating onto) heavy fluid."

c.f. Taylor's paper.

i.e. in frame of ablator:

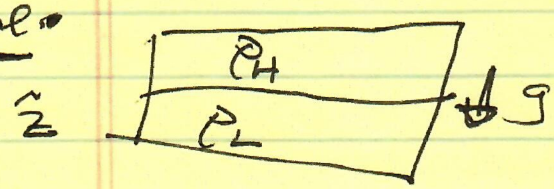


$\Rightarrow$ equivalent to



Both cases: $\nabla P \, \nabla \rho < 0$

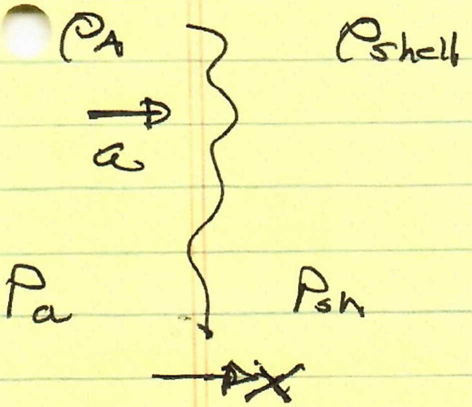
i.e.



$\nabla \rho > 0$

$\nabla P < 0$.

$\nabla P = -\rho g$



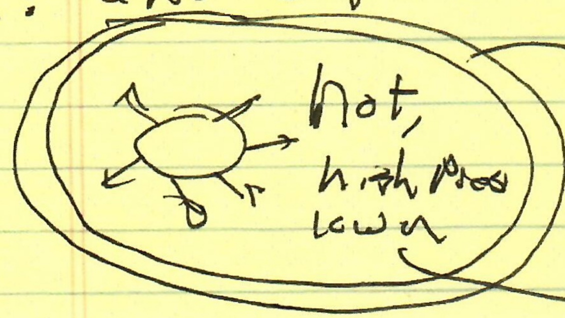
$\nabla_x \rho \quad 0$

$\nabla_x P < 0$.

$P_a > P_{shell}$

i.e. both $\nabla P \cdot \nabla \rho < 0$

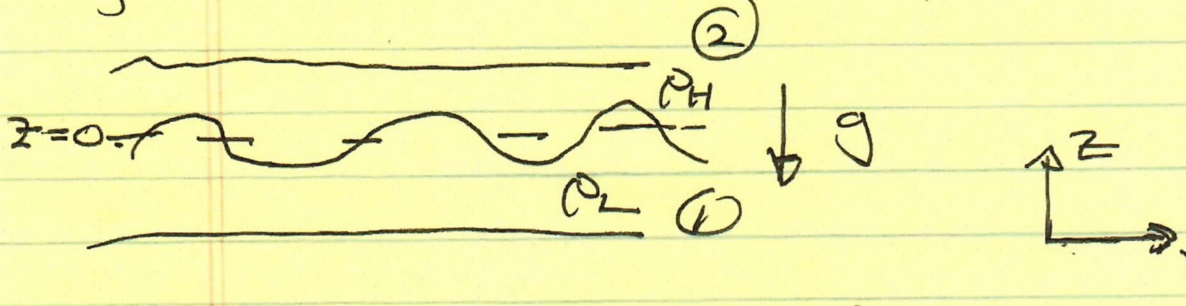
n.b.: also supernovas



colder, high density material

hot, low density high pressure

so, hereafter: simple case



— $\underline{\nabla} \cdot \underline{V} = 0$ i.e. ($\gamma \ll$ ... etc.)

— ideal fluid (add visc. on HW)

Equilibrium

$$\frac{\partial \underline{v}}{\partial t} + \underline{v}\cdot\underline{\nabla}\,\underline{v} = -\frac{\underline{\nabla} p}{\rho} + \rho\,\underline{g}$$

ρ const.

$v \to 0$

$$\nabla^2 p = 0$$

$\to$ vert, $\partial_z^2 p = 0$

$$p = p_0 + p' z$$

but $dp/dz = -\rho g$

$$p_2' = -\rho_2 g$$

$$p_1' = -\rho_1 g$$

$\Delta \rho > 0$

going $\downarrow$

so interface ($k_x L_z \ll 1$), vorticity localized on interface. So treat fluid as irrotational

$$\underline{\omega} = 0 , \qquad \underline{V} = \underline{\nabla} \phi$$

$$\underline{\nabla} \cdot \underline{V} = 0 \qquad \nabla^2 \phi = 0$$

$$e^{-kz}$$

— — — — $z = 0$

$$e^{+kz}$$

$$\phi = \sum_k e^{ikx} \phi_k(z)$$

$$\left(\partial^2 / \partial z^2 - k^2 \right) \phi_k(z) = 0$$

$$\phi_k = \begin{cases} e^{-kz} & z > 0 \\ e^{kz} & z < 0 \end{cases} \qquad (k > 0)$$

at interface ($z = 0$) = matching conditions

→ pressure balance across interface

$$P(0_+) = P(0_-)$$

(else interface in motion on acoustic time scales)

$$V_z(0_+) = V_z(0_-)$$

$$\left.\frac{\partial\phi}{\partial z}\right|_{2,\ z\to 0} = \left.\frac{\partial\phi}{\partial z}\right|_{1,\ z\to 0}$$

i.e.

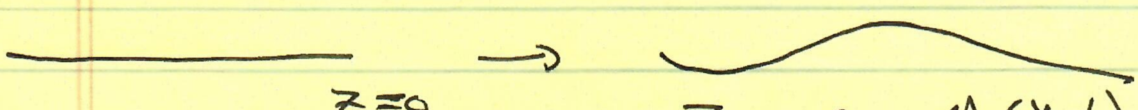
$$\int_{0_-}^{0_+}\left[\frac{\partial^2\phi}{\partial z^2} - k^2\phi\right] = 0$$

Note: V_z b.c. immediately forces

$$-k\phi_2 = k\phi_1 \quad\Rightarrow\quad \phi_2 = -\phi_1$$

What of dynamics?

— interface ripples



$$z_i = 0 + \eta(x,t)$$

— displacement of interface

— η specifies interface position

Note: $\phi = \phi(x, z_i, t)$ $\left\{ \begin{array}{l} \text{at interface} \\ \text{position} \end{array} \right.$

$= \phi(x, 0+\eta, t)$

linear theory

$\cong \phi(x, 0, t)$

i.e. linear theory $\left\{ \begin{array}{l} \phi(x, z_i, t) \to \phi(x, 0, t) \\ k\eta \ll 1 \end{array} \right.$

Now must account for force of gravity with displaced interface in Bernoulli equation:

$$\rho\left(\frac{\partial \underline{v}}{\partial t} + \underline{v}\cdot\underline{\nabla}\,\underline{v}\right) = -\underline{\nabla} p - \rho\,\underline{g}$$

$$\rho\left(\frac{\partial}{\partial t}\underline{v} + \underline{\nabla}\left(\frac{v^2}{2}\right) - \cancelto{0}{\underline{v}\times\underline{\omega}}\right) = -\underline{\nabla} p - \rho g \hat{z}$$

$(g > 0)$

$\underline{v} = \underline{\nabla}\phi$, $v_z = \partial_z \phi$

$\int_0^\eta dz\, v_{z_1} = \phi_1$, $\int_\eta^0 dz\, v_{z_2} = \phi_2$

so

$$\boxed{\frac{\partial \phi}{\partial t} + \frac{(\underline{\nabla}\phi)^2}{2} = -\frac{p}{\rho} - g\eta}$$

absent gravity, $p = -\rho\, \partial\phi/\partial t$

so $$p = -\rho g z - \rho \frac{\partial \phi}{\partial t}$$

and ~ at surface.

$$p = -\rho g \eta - \rho \frac{\partial \phi}{\partial t}$$

and finally have equation / dynamic boundary condition for displacement:

$$\boxed{\frac{d\eta}{dt} = \partial_z \phi \Big|_0 = v_z}$$

$\Rightarrow$

$$\frac{\partial \eta}{\partial t} + \underbrace{\underline{v}}_{\nabla\phi} \cdot \underline{\nabla}\, \eta = \frac{\partial \phi}{\partial z}\Big|_0$$

For stability: linearize

$$\frac{\partial \tilde{\phi}}{\partial t} = -\frac{\tilde{p}}{\rho} - g\eta$$

$$\frac{\partial \tilde{\eta}}{\partial t} = \frac{\partial \tilde{\phi}}{\partial z}\Big|_0 .$$

ρ_H ②

ρ_L ①

So noting $\rho_2 \approx \rho_1$

$$\tilde{p}^{(1)}\Big| = \tilde{p}^{(2)}\Big|$$

$$\tilde{\phi}^{(1)}\Big|_0^0 = -\phi^{(2)}\Big|_0^0$$

$$\rho_2 \frac{\partial \tilde{\phi}^{(2)}}{\partial t} + g\rho_2 \tilde{\eta} = \rho_1 \frac{\partial \tilde{\phi}^{(1)}}{\partial z} + g\rho_1 \tilde{\eta}$$

$$g(\rho_2 - \rho_1)\tilde{\eta} = \rho_1 \frac{\partial \tilde{\phi}^{(1)}}{\partial t} - \rho_2 \frac{\partial \tilde{\phi}^{(2)}}{\partial t}$$

$$= (\rho_1 + \rho_2) \frac{\partial \tilde{\phi}^{(1)}}{\partial t}$$

$$\boxed{\begin{aligned} \frac{\partial \tilde{\phi}^{(1)}}{\partial t} &= g\left[\frac{(\rho_2 - \rho_1)}{(\rho_2 + \rho_1)}\right]\tilde{\eta} \\ \frac{\partial \tilde{\eta}}{\partial t} &= \frac{\partial \tilde{\phi}^{(1)}}{\partial z}. \end{aligned}}$$

$$\Rightarrow \boxed{\frac{\partial^2 \tilde{\phi}^{(1)}}{\partial t^2} = g\left[\frac{(\rho_2 - \rho_1)}{(\rho_1 + \rho_2)}\right]\frac{\partial \tilde{\phi}^{(1)}}{\partial z}.}$$

using $\phi \sim e^{-i\omega t} e^{kz} e^{ikx}$

$$\Rightarrow -\omega^2 = \left[g(\rho_2 - \rho_1) / (\rho_1 + \rho_2) \right] k.$$

$\rho_2 = \rho_H$
$\rho_1 = \rho_L$

$$\boxed{\gamma^2 = gAk \;,\; A = \frac{\rho_H - \rho_L}{\rho_H + \rho_L}}$$

– free energy
– inertia

Atwood #

i.) $\rho_H = H_2O$ $\quad \lambda \sim 1$ cm.
$\rho_L =$ air $\quad \tau_g \sim .1$ sec.

(fast!)

ii.) $\rho_2 =$ air $\quad \rho_{air}/\rho_{H_2O} \to 0$
$\rho_1 =$ water

$$\omega = \sqrt{kg}$$

$\Rightarrow$ dispersion relation for surface gravity wave.

(stable wave counterpart of R-T)

iii) $\gamma \sim (gAk)^{1/2}$

→ shorter wavelengths grow faster?!

⇒ small scale effects?
cut-off, regulator?

— viscosity (HW)

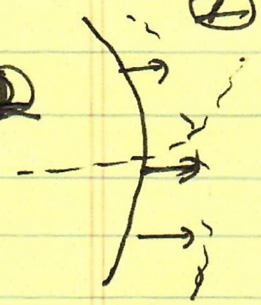
— surface tension #

— finite layer width ($k_y L_z \gtrsim 1$)

Surface Tension → force due increase in surface area interface

P_1 ② P_2

①



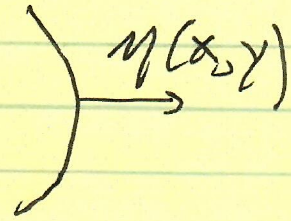
① expands

↳ isothermal displacement

$$\underbrace{dF}_{\text{change in free energy}} = -\underbrace{P_1 dV}_{\text{① expands into ②}} - P_2(-dV) + \underbrace{\sigma dA}_{\text{change in surface area of interface}}$$

$dV = dA\, d\eta$

displacement



so

$$dA = \int dx\,dy\left(1+\left(\frac{\partial\eta}{\partial x}\right)^2+\left(\frac{\partial\eta}{\partial y}\right)^2\right)^{1/2} - \int dx\,dy$$

small displacement (slope):

$$\simeq \int dx\,dy\left(1+\frac{1}{2}\left(\frac{\partial\eta}{\partial x}\right)^2+\frac{1}{2}\left(\frac{\partial\eta}{\partial y}\right)^2\right) - \int dx\,dy$$

$$= \int dx\int dy\ \frac{1}{2}\left[\left(\frac{\partial\eta}{\partial x}\right)^2+\left(\frac{\partial\eta}{\partial y}\right)^2\right]$$

IBP

$$= \int dx\int dy\ (\underbrace{-\nabla^2\eta}_{\text{curvature of surface displacement}})\, d\eta$$

so

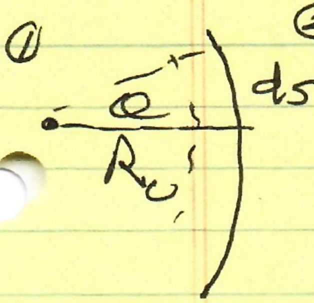
$$dF = \int\left[(\rho_2-\rho_1)\,dA_0 - \sigma\nabla^2\eta\, dA_0\right]\delta\eta$$

so criterion for equilibrium:

$$\boxed{P_2 - P_1 = \sigma \nabla^2 \eta}$$

More generally: $$dF = (P_2 - P_1)\, dA_0\, d\eta + \sigma\, dA$$

Now consider arbitrary (i.e. not "weakly curved" interface):



$$ds = (R_0 + d\eta)\, d\theta$$

$$\simeq dl_0 \left(1 + d\eta / R_1\right)$$

radius curv

In general, surface parametrized by $\underline{\underline{2}}$ radii of curvature, R_1, R_2:

$$dA = \int dl_1\, dl_2 \left(1 + \frac{d\eta}{R_1}\right)\left(1 + \frac{d\eta}{R_2}\right) - \int dl_1\, dl_2$$

$$= \int dl_1\, dl_2 \left(1/R_1 + 1/R_2\right) d\eta$$

so

$$dF = \int \left[(P_2 - P_1) + \sigma\left(1/R_1 + 1/R_2\right)\right] dA_0\, d\eta.$$

so, for equilibrium with interface (general)

$$\boxed{\sigma\left(1/R_1 + 1/R_2\right) = P_1 - P_2}$$ [Laplace's Law]

- Given 2-phase equilibrium (separate domains), can use Laplace Law to estimate droplet size for immiscible liquids

i.e. $P_1 > P_2 \Rightarrow R \sim \sigma/(P_1 - P_2)$

Now, back to R-T, S-W: $\rho_H \gg \rho_L$, $\rho_H + \rho_L \to \rho_H$

$$P \to P - \rho \gamma_T \nabla_h^2 \eta$$

$\gamma_T \equiv \sigma/\rho$. $\to \sigma$ for each interface i.e. water-air, etc.

$\Rightarrow$

$$\gamma_{R-T} = \left(kgA - \underbrace{\gamma_T k^3}_{\text{cut-off}}\right)^{1/2}$$

$$k_{max}\Big|_{unst} \sim \left(g/\gamma_T\right)^{1/2}$$ $\to$ limits range of unstable modes.

For stable case:

$$\omega^2 = gk + \frac{\sigma}{\rho} k k^2 \quad \Big\} \text{ gravity-capillary}$$

$gk \downarrow$ gravity wave (long)

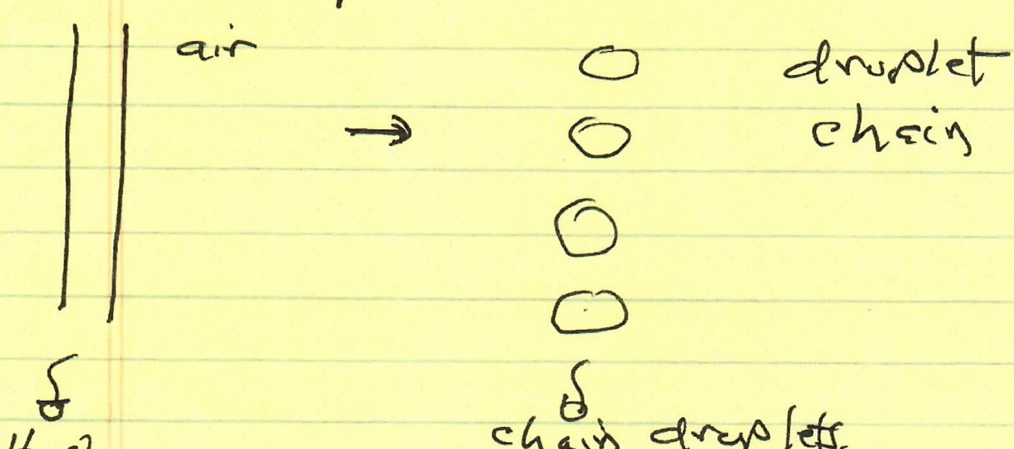
$\frac{\sigma}{\rho} k k^2 \downarrow$ capillary wave (short)

$l_{cap} \sim (\sigma/\rho g)^{1/2}$

{ in ocean cross-over at few cm.
Capillarity important at ≤ 5 cm.

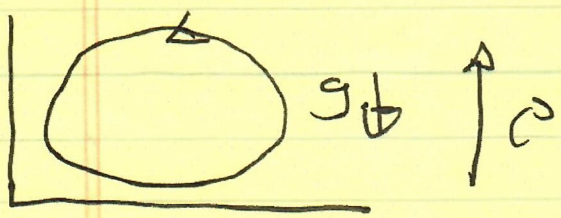
N.B.:

Capillarity (S.T.) can induce instability — classic is line of fluid break-up to string of pearls



akin sausage instability in MHD

Note also:



Finite layer thickness

$\Rightarrow$ 2D cell - distributed vorticity

$$\omega^2 = -\frac{k_x^2}{k_x^2 + k_z^2} \, g \, \frac{1}{\rho} \frac{\partial \rho}{\partial z}$$

$$= -\frac{k_x^2}{k^2} \, g / L_\rho$$

$$\gamma^2 = \left(\frac{k_x^2}{k^2} \, g / L_\rho \right)^{1/2}$$, so $\gamma \uparrow$ to flat.

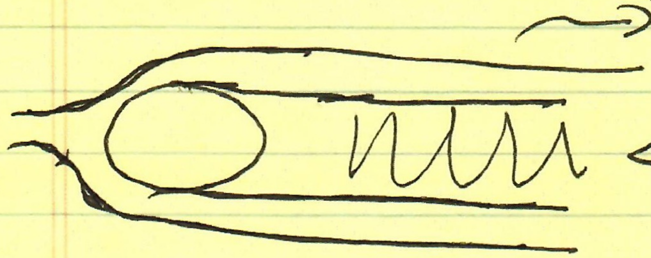
- stable stratification:

$$\omega^2 = \frac{k_x^2}{k^2} \, g / L_\rho$$ → internal wave.

$N^2 \rightarrow$ BV freq.

→ Kelvin - Helmholtz stability of discontinuity!

Recall OV of main story:



- with no-slip B.C.'s,

$V_n|_{surf} = v_T|_{surf} = 0$

separation happens, wake forms

- separation → instability → turbulence.

How?

Instability ⇒ Kelvin - Helmholtz

⇒ free energy → ∇V - flow shear

⇒ simplification: shear layer (interface) idealization

$v_x = V$

ρ_1

$v_x = 0$

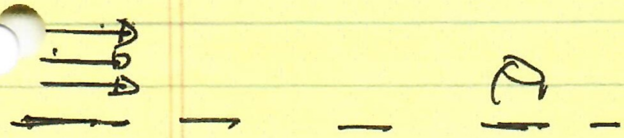
ρ_2

Note: { classic example of interfacial instability.

- $\nabla V = 0$, except interface
- vorticity $\partial V_x / \partial z$ localized to interface

$\Rightarrow$ can play game à la R–T, now with $\underline{V}$, η.

<u>Physical ideas</u>: ①



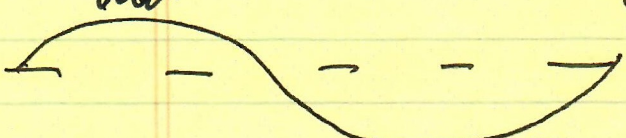
① high V, low P

② low, zero V, high P

$$p + \rho V^2/2 = \text{const}$$

② δV perturbation
→ ripple interface

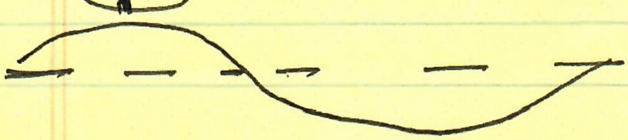
⊖ bring in slow fluid — slow δV



⊕ speeds up → fast drift in

so Bernoulli ⇒

$\delta p > 0$ ⊕ δP

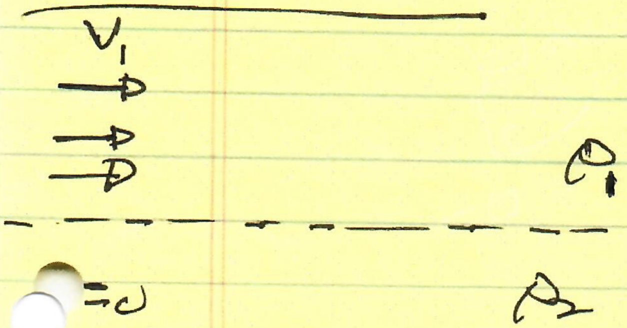


⊖ $\delta p < 0$

$\delta p > 0 \Rightarrow \delta v < 0$, further unstable — i.e. re-enforces critical perturbation

$\Rightarrow$ KH instability drives viscous mixing via turbulence, mixing, billows, etc.

To calculate:



$p + \frac{V^2}{2} = \text{const}$ assumes eqbrm.

so, as before:

$\nabla \cdot \underline{V} = 0$

$\underline{V} = \nabla \phi$ $\qquad \underline{\omega} = 0$, except interface

$\nabla^2 \phi = 0$

$\Rightarrow$ wave along interface

$$\phi = \sum_k \phi_k \, e^{ikx} \, e^{-k|z|} \, e^{-i\omega_k t}$$

decays away from interface.

as before; and $\left.\frac{\partial \phi}{\partial z_1}\right|_0 = \left.\frac{\partial \phi}{\partial z_2}\right|_0$

$\rightarrow \tilde{P}_1(0_+) = \tilde{P}_2(0_-) \Leftarrow \phi$ continuity

define

$\rightarrow \eta \underline{\underline{\Rightarrow}}$ interface ripple/displacement

$\eta = \eta(x,t)$

$\frac{d\eta}{dt} = V_z\Big|_0 \leftarrow V_z(x, 0+\eta)$

$$\frac{\partial^2 \phi}{\partial z^2} - k_z^2 \phi = 0$$

and $V_z(0_+) = V_z(0_-)$

$\Rightarrow \phi'_+ = \phi'_-$

Now, $\frac{\partial}{\partial t}\underline{V} + \underline{V}\cdot\underline{\nabla}\,\underline{V} = -\frac{\underline{\nabla} P}{\rho}$

$$\rho_{\frac{1}{2}}\left(\frac{\partial}{\partial t}\tilde{V}_{z_{\frac{1}{2}}} + V_{\frac{1}{2}}\partial_x \tilde{V}_{z_{\frac{1}{2}}}\right) = -\nabla_z P_{\frac{1}{2}}$$

$\hookrightarrow$ but $\nabla_z P \rightarrow \mp\, {}^{1}_{2}$

$$\tilde{V}_{z_{\frac{1}{2}}} = \mp \frac{ik\tilde{P}_{\frac{1}{2}}}{\rho_{\frac{1}{2}}(kV_{\frac{1}{2}} - \omega)}$$

and

$\partial_z P \sim$ evanescent

N.B. $\tilde{V}_z$, so i from ∂_t, ∂_x only

$$\frac{d\eta}{dt} = \frac{\partial\tilde{\eta}}{\partial t} + V\frac{\partial\tilde{\eta}}{\partial x} = \tilde{V}_{z,}$$

$$-i(\omega - kV)\tilde{\eta}_k = \tilde{V}_{zk} \quad \#1$$

so using Euler/Bernoulli

$$-i(\omega - kV)\tilde{\eta}_k = \frac{-ik\tilde{P}_1}{\rho_1(kV-\omega)}$$

so

$$\tilde{P}_{1k} = \frac{-\rho_1(kV-\omega)^2}{k}\tilde{\eta}_k$$

$$\tilde{P}_{2k} = \frac{\rho_2\omega^2}{k}\tilde{\eta}_k$$ ← note sign!

(opposite signs $\tilde{\phi}_1, \tilde{\phi}_2$)

$$-k\phi_1 = k\phi_2$$

and $\tilde{P}_1 = \tilde{P}_2 \Rightarrow$

$$\boxed{-\frac{\rho_1}{k}(kV-\omega)^2 = \frac{\rho_2}{k}\omega^2}$$

$$\Rightarrow \boxed{\omega = kV\left(\frac{\rho_1 + i(\rho_1\rho_2)^{1/2}}{\rho_1+\rho_2}\right)}$$

$$\Rightarrow \gamma \sim kV \frac{\sqrt{\rho_1\rho_2}}{\rho_1+\rho_2}$$ $\rightarrow$ KH growth

note $\omega_r \sim kV \left(\rho_1 / (\rho_1+\rho_2)\right)$

no "exchange of stabilities" here.

$\sim \rho_1 = \rho_2 \quad \gamma \simeq \frac{kV}{2}$

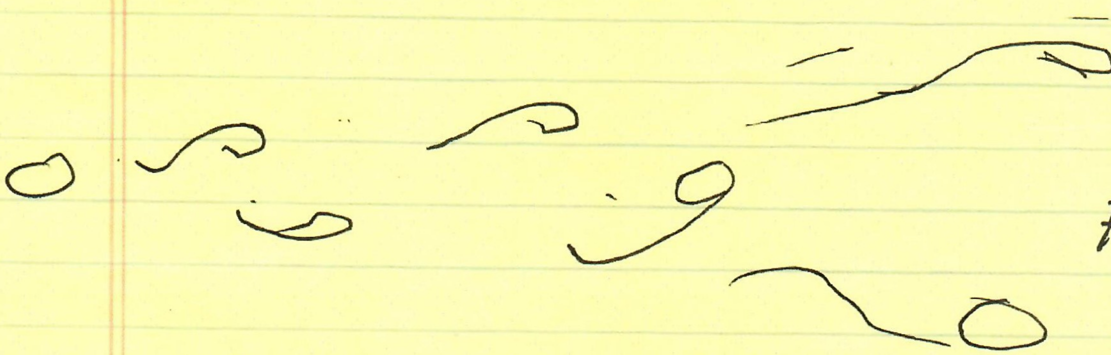
generally $\boxed{\gamma \sim k(\Delta V)}$

→ what happens?

→ vortex roll-up, billows

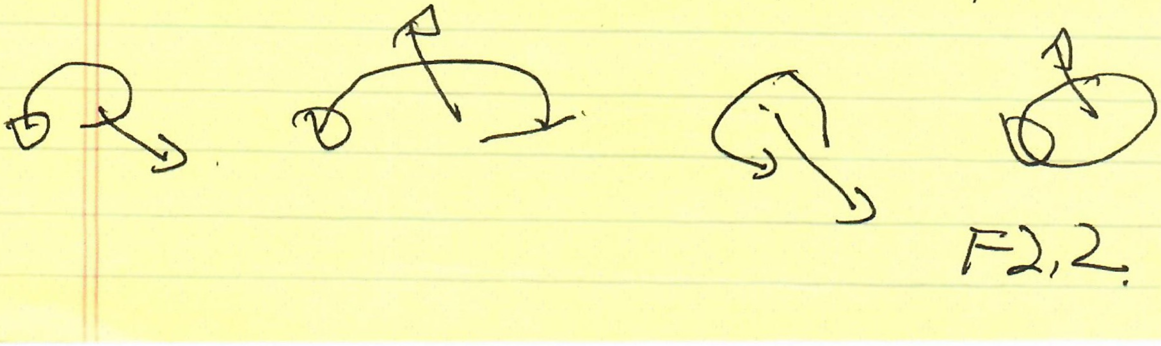
F 2.3, F 2.4

→ Van-Karman vortex street



F1.15

→ n.b. array vortex lines unstable w/r displacements as shown



F2.2

Refs:

→ R-T, K-H:

· S. Chandrasekhar, "Hydrodynamic and Hydromagnetic Stability"

→ K-H: Falkovich

→ Surface Waves, Surface Tension (Laplace Law), K H: Landau/Lifshitz.

· see also: G. K. Batchelor, "An Introduction to Fluid Mechanics"