

Lecture Notes on Fluid Dynamics
(1.63J/2.21J)
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5.3 Inviscid instability mechanism of parallel flows

We now turn to an older problem of the instability of parallel flow without stratification and gravity, such as channel flows, jets, wakes and boundary layers.

5.3.1 Rayleigh's equation

In a shear flow a necessary condition for instability is that there must be a point of inflection in the velocity profile $U(z)$, i.e.,

$$\frac{d^2U}{dz^2} = 0 \quad (5.3.1)$$

somewhere in the flow.

Let us begin with an inviscid uniform flow.

$$\vec{U} = U\vec{i}, \quad P = 0 \quad (5.3.2)$$

and add an infinitesimal disturbance so that the total velocity and pressure fields are

$$(u, w, p) = (U + u', w', p') \quad (5.3.3)$$

where primes denote disturbances which are functions of (x, z, t) . The governing equations are

$$u'_x + w'_z = 0 \quad (5.3.4)$$

$$\rho(u'_t + (U + u')u'_x + w'(U'_z + u'_z)) = -p'_x \quad (5.3.5)$$

$$\rho(w'_t + (U + u')w'_x + w'w_z) = -p'_z \quad (5.3.6)$$

The boundary conditions are

$$w' = 0, \quad z = 0, d \quad (5.3.7)$$

where d can be unbounded.

Linearizing the momentum equations by omitting terms quadratic in disturbances, we get

$$\rho \left(u'_t + Uu'_x + \frac{dU}{dz}w' \right) = -p'_x \quad (5.3.8)$$

$$\rho(w'_t + Uw'_x) = -p'_z \quad (5.3.9)$$

Eliminating p' by cross-differentiation,

$$\rho \left(u'_t + Uu'_x + \frac{dU}{dz}w' \right)_z = -p'_{xz} = \rho(w'_t + Uw'_x)_x$$

Introducing the stream function by $u' = \psi_z, w' = -\psi_x$, we get

$$\left(\psi_{zt} + U\psi_{xz} - \frac{dU}{dz}\psi_x \right)_z = (-\psi_{xt} + U\psi_{xx})_x$$

Let us consider a wave like disturbance

$$\psi = f(z)e^{ik(x-Ct)}, \quad \text{where } C = \frac{\omega}{k} \quad (5.3.10)$$

then

$$\left(-ikCf_z + ikUf_z - ik\frac{dU}{dz}f \right)_z = ik(k^2Cf + k^2Uf)$$

or

$$(U(z) - C)(f_{zz} - k^2f) - U_{zz}f = 0. \quad (5.3.11)$$

which is known as Rayleigh's equation in hydrodynamic instability. The boundary conditions are:

$$f = 0, \quad z = 0, d \quad (5.3.12)$$

5.3.2 Rayleigh's necessary condition for instability

Let us rewrite (5.3.11) as

$$f_{zz} - k^2f - \frac{U_{zz}}{U-C}f = 0 \quad (5.3.13)$$

and multiply by the complex conjugate

$$f^*(f_{zz}) - k^2ff^* - \frac{U_{zz}}{U-C}ff^* = 0$$

which can be rewritten by partial integration

$$\frac{d}{dz}(f^*f_z) - |f_z|^2 - k^2|f|^2 - \frac{U_{zz}}{U-C}|f|^2 = 0$$

Integrating from $z = 0$ to $z = d$ and applying the boundary conditions we get simply

$$\int_0^d dz \frac{U_{zz}}{U-C}|f|^2 = - \int_0^d dz (|f_z|^2 + k^2|f|^2) \quad (5.3.14)$$

Now we let $C = C_r + iC_i$ to be complex, then on the left-hand side,

$$\frac{U_{zz}|f|^2}{U-C} = \frac{U_{zz}(U-C^*)|f|^2}{|U-C|^2} = \frac{U_{zz}(U-C_r+iC_i)|f|^2}{|U-C|^2}$$

Equation (5.3.14) becomes

$$\int_0^d dz \frac{U_{zz}(U-C_r+iC_i)|f|^2}{|U-C|^2} = - \int_0^d dz (|f_z|^2 + k^2|f|^2) \quad (5.3.15)$$

We get from the imaginary part of (5.3.15),

$$\int_0^d dz \frac{U_{zz} |f|^2}{|U - C|^2} = 0 \quad (5.3.16)$$

if $C_i \neq 0$. Thus for instability it is necessary that U_{zz} is positive for some y and negative elsewhere, i.e., U_{zz} must vanish somewhere in the flow, i.e., the velocity profile must have an inflection point inside the flow. This is Rayleigh's necessary condition for instability.

5.3.3 Physical explanation (Lin, 1945)

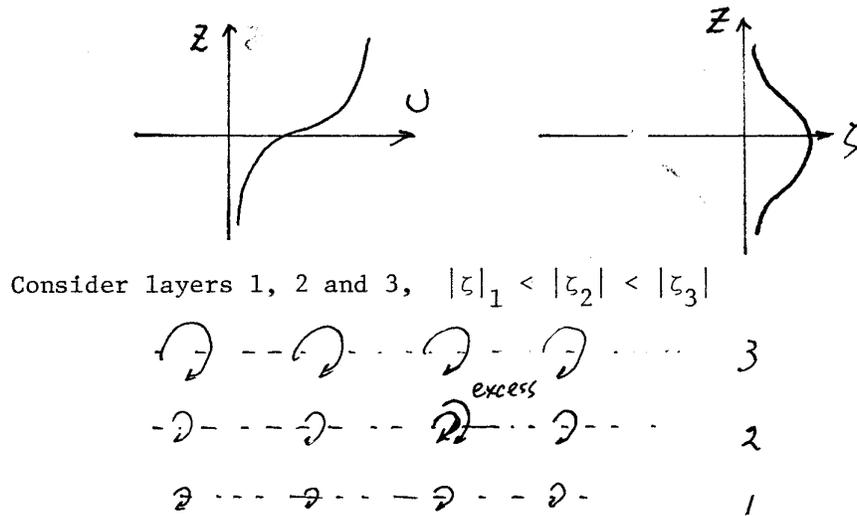


Figure 5.3.1: (a) Velocity profile with an inflection point. (b) Vorticity profile. (c) Effect of exchanging fluid parcels on vorticity

In Figure 5.3.1 we sketch the velocity profile with an inflection point at $z = 0$ and the corresponding profile of vorticity $\zeta = U_z$ which has a maximum at $z = 0$. (Note that in the right-handed system the y axis points into the paper, therefore the flow of a positive vortex is clockwise.)

Consider three layers in the region where $U(z)$ increases with z monotonically, i.e., below the inflection point, with $\zeta(z_1) < \zeta(z_2) < \zeta(z_3)$. If a fluid parcel descends from level 3 to level 2, it brings with it its vorticity without change, according to the vorticity transport law in an inviscid fluid. An excess vorticity is created at level 2 which tends to replace the fluid on the right in layer 2 by fluid with higher vorticity, and the fluid on the left in layer 2 by fluid with lower vorticity. The net consequence is to force the original excess vortex to return to layer 3. Similarly, if a fluid parcel ascends from level 1 to level 2, it brings with it

vorticity, hence creates an excess vorticity defect with tends to replace the fluid on the left in layer 2 by fluid with higher vorticity, and the fluid on the right in layer 2 by fluid with lower vorticity. The net consequence is to force the original defect vortex to return to layer 3. Thus an accidental displacement of a fluid parcel tends to its original level; the flow is stable.

By a similar reasoning, if $U(z)$ decreases monotonically in z the flow is also stable. However, if there is a level of vorticity extremum, say level 0 at $z = 0$, then a fluid element arriving at this layer is not forced back to its origin. A fluid element on one side of level 0 is equally at home on the opposite side. The flow is unstable.

5.3.4 Fjortoft's stronger condition

Further information can be obtained from the real part of (5.3.15),

$$\int_0^d dz \left(\frac{U_{zz}(U - C_r)}{|U - C|^2} \right) |f|^2 = - \int_0^d dz (|f_z|^2 + k^2 |f|^2) \quad (5.3.17)$$

Now let U_I be the velocity at the point of inflection, we use (5.3.16) so that

$$\int_0^d dz \frac{U_{zz}(U_I - C_r)|f|^2}{|U - C|^2} = 0 \quad (5.3.18)$$

The difference of (5.3.17) and (5.3.18) is

$$\int_0^d dz \frac{U_{zz}(U - U_I)}{|U - C|^2} |f|^2 = - \int_0^d dz (|f_z|^2 + k^2 |f|^2) < 0 \quad (5.3.19)$$

For this to hold it is necessary that the product

$$U_{zz}(U - U_I) < 0 \quad (5.3.20)$$

for all z in the flow. For implications of Fjortoft's theorem, see Figure 5.3.2. Jets and wakes satisfy Rayleigh-Fjortoft criterion, but Poiseuille flows in a pipe and boundary layers on a flat plate do not. Why then is Poiseuille flow known to be unstable beyond $Re = 2100$ (Reynolds)?

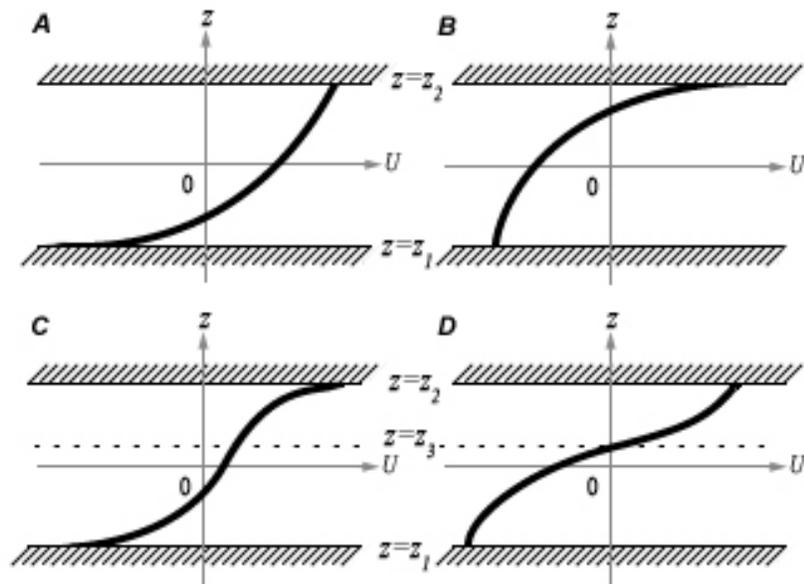


Figure 5.3.2: Fjortoft Theorem