5.1 Boundary Layer Transition

Transition is the process by which a laminar flow becomes turbulent. In most cases, a laminar flow will become turbulent when the Reynolds number increases above a certain value. The following images are reconstructions of the Reynolds experiment in the 1880s. Dye was injected along the centreline of a pipe through which water flows steadily. In the top image, the dye remained along the centreline, indicating laminar flow. As $Re$ was increased, the flow underwent transition (middle image) and eventually became turbulent (bottom image).
Transition is a very complex process and its prediction remains a topic of intense research. Transition may be triggered by various types of flow disturbances, which could be due to the following causes:

- wall roughness or obstructions (boundary layer trips)
- free stream turbulence
- acoustic noise, namely, pressure fluctuations
- pressure gradient
- surface heating or cooling
- suction or blowing of fluid from the wall
- wall curvature
- compressibility
- many other sources of disturbances.

**By-pass transition:** In most engineering applications, there are sufficient disturbances for a laminar flow at fairly high Reynolds numbers to occur almost spontaneously; this phenomenon is called by-pass transition and occurs when \( Re_x \) reaches or exceeds a transition value \( Re_{xtr} \). A laminar boundary layer over a flat plate in a flow with constant pressure will typically undergo by-pass transition when \( Re_{xtr} \approx 5 \times 10^5 \).

**Natural transition:** In flows generated carefully in the laboratory or in some environmental flows which are subjected to extremely low levels of disturbances, it is possible for a boundary layer to remain laminar as \( Re \) increases well beyond values for by-pass transition. This will happen when the wall is very smooth and disturbances of all sorts (vibrations, free-stream turbulence, strong adverse pressure gradients etc.) are absent. Under such conditions, transition will occur gradually and will occupy a long stretch of the flow. This type of transition is called natural transition. For a thin, smooth plate with \( dp/dx = 0 \), the critical Reynolds number for natural transition is typically \( Re_{xtr} \approx 5 \times 10^6 \).

**Steps for natural boundary layer transition on a flat plate:** As \( Re_x \) increases, the flow becomes unstable and waves (Tollmien-Schlichting waves) with a preferred spacing appear in it. Eventually, isolated turbulent spots (Emmons spots) appear in the flow and grow downstream. These spots coalesce and give way to full turbulence far away from the location where instability was first noticeable.
104. Instability of the boundary layer on a plate. At $R = 20,000$ based on length (upper photograph) the boundary layer is laminar over a flat plate aligned with the stream. At $R = 100,000$ (lower photograph) two-dimensional Tollmien-Schlichting waves appear. They are made visible by colored fluid in water. ONERA photograph, Werle 1980

105. Natural transition on a slightly inclined plate. At the same Reynolds number of 100,000 but $1^\circ$ angle of attack, transition to turbulence occurs on the plate. ONERA photograph, Werle 1980
109. Emmons turbulent spot. On a flat plate, transition from a laminar to a turbulent boundary layer proceeds intermittently through the spontaneous random appearance of spots of turbulence. Each spot grows approximately linearly with distance while moving downstream at a fraction of the free-stream speed, and maintaining the characteristic arrowhead shape that is shown here by a suspension of aluminum flakes in water. Transverse contamination is seen spreading from the bottom of the channel. At the center of the spot the Reynolds number is 200,000 based on distance from the leading edge. Cantwell, Coles & Dimotakis 1978
Prediction of by-pass transition:

In general, prediction of the exact location at which transition occurs is quite difficult.

Michel’s criterion for a smooth wall (modified version):

Transition would occur when

\[
\text{Re}_\theta \geq 1.174 \left(1 + \frac{22400}{\text{Re}_x}\right) \text{Re}_x^{0.46}
\]

where \( \text{Re}_\theta = \frac{\theta u_e}{\nu} \), \( \text{Re}_x = \frac{u_e x}{\nu} \). This criterion has been validated for \( 10^5 < \text{Re}_x < 4 \times 10^7 \).

Rough estimate for transition on airfoils:

At large Re, a laminar boundary layer will undergo transition as soon as, or very shortly after, it is exposed to an adverse pressure gradient. Thus, transition of laminar boundary layers on the upper surfaces of airfoils may be assumed to occur at the point of minimum pressure, unless of course other methods predict transition to occur upstream of this location.