Mechanisms of Laminar-to-Turbulent Transition

Master, specialization course
3 lecture hours/week (3 SWS), 6 LPs/ECTS

Lecturer:
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Contents of Lecture

1 Introduction (with movies/pics) and Transition Road Map

2 Primary-Instability Concept (Linear Stability Theory, LST)
   2.1 Nonlinear disturbance equation
   2.2 Basic stability and disturbance growth definitions
   2.3 Small wave-like disturbances and modal exponential growth:
      Orr-Sommerfeld Equation (OSE)
   2.4 Rayleigh’s and Fjortoft’s criteria, Squire theorem, OSE solution interpretation
   2.5 Analytical example: the piecewise linear mixing layer
   2.6 Results for self-similar boundary layers with pressure gradient and wing profiles

3 Transition prediction based on e-to-the-N-method

4 Instability Influencing Parameters
   4.1 Suction, wall temperature
   4.2 Compressibility/Mach number
   4.3 Self-induced crossflow in swept-wing boundary layer
   4.4 Non-modal (transient, algebraic) growth, Tu level, (discrete) roughness
   4.5 Final remarks and literature for §2-§4
Contents of Lecture

5 Secondary-Instability (SI), dynamical-structure formation and laminar breakdown
  5.1 Spectral secondary instability and the classical breakdown scenarios
  5.2 Localized (secondary) instability, crossflow-vortex-/streak-induced breakdown
  5.3 Turbulent spot, complex disturbances

6 Transition Control
  6.1 Laminar Flow Control
  6.2 Turbulence triggering
  6.3 Notes on actuators
  6.4 Final remarks and literature for §5-§6
Standard scenario (A) for a 2-d flat-plate boundary layer

oncoming disturbances

roughness, vibrations

receptivity

boundary-layer thickness

primary instability

secondary instability

turbulence randomization

for small initial disturbances: Tollmien-Schlichting waves

fundamental / subharmonic resonance, \(\Lambda\) vortices
2.6 OSE, results, 1

- Orr-Sommerfeld equation: TS-waves that represent downstream travelling “infinitely small counterrotating spanwise vortices” can grow exponentially in a boundary layer
- Stability diagram (2-d waves): instability inside “banana”, see below [5]
- Strong “inviscid” instability if $U(y)$ has an inflection point (IP) and here the spanwise vorticity ($\sim|dU/dy|$) has a maximum as, e.g., for Falkner-Skan profiles with $\beta_H<0$
- Without IP: only viscous instability; the diagram closes for large $Re$ because $dU/dy \sim \delta^{-1}$

\[
\begin{align*}
\frac{dP}{dx} &> 0, \\
\frac{dP}{dx} &= 0, \\
\frac{dP}{dx} &< 0, \text{ or suction}
\end{align*}
\]

\[
\begin{align*}
\alpha, \omega &
\end{align*}
\]

\[
\begin{align*}
\text{viscosity destabilizes} &
\text{branch II (end of amplification)}
\end{align*}
\]

\[
\begin{align*}
\text{stable} &
\text{unstable}
\end{align*}
\]

\[
\begin{align*}
\text{branch I} &
\text{with IP} \\
\text{without IP} &
\text{inviscid instability}
\end{align*}
\]

\[
\begin{align*}
\text{lower } Re_{crit} &
\end{align*}
\]
2.6 Wing profiles, experiment, 1

Position of boundary-layer instability onset (left) and transition (right) on a wing profile as function of chord Re number and lift coefficient $c_l$. $A$ - boundary-layer separation for laminar flow until $A$; $M$ - pressure minimum; $S$ - stagnation point. For $Re_L \leq 5 \times 10^6$ transition occurs downstream of or around $M$ [2].
5.1 SSI and classical breakdown scenarios, 12

- Visualizations in experiments, Blasius flow (smoke, laser light sheet)

\[ K \text{-Typ (Saric 1984, see [12])} \]

\[ H \text{-Typ (Saric 1984, see [12])} \]

\[ O \text{-Typ (Wiegel, Bippes 1997, see [28])} \]

\[ 3-d \text{ waves} \]

\[ \text{streaks (0.2)} \]
5.1 Structure formation and breakdown scenarios, 15 (DNS)  

- Details of $K$-Breakdown (with adverse pressure): spanwise vorticity / shear-layers [25, 27]

Snapshots during one fundamental time period with downstream rolling separation zone due to large-amplitude 2-d TS wave in the decelerated Falkner-Skan-layer: Does not appear with Blasius flow, falsifying fig. 16.14 in [2].

peak plane /$\Lambda$-head plane ($z=z_0$) … between $\Lambda$‘s ($z_0+\lambda z/2$), here not valley but co-peak plane

vortex ring ejection $\rightarrow$

causes spikes in $u$-signal

and is very sensitive to

background disturbances

$\rightarrow$ randomization

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5.2 LSI/Crossflow breakdown, 5

- Steady-crossflow-vortex induced breakdown in a 3-d boundary layer on a swept wing
- The subsequent DNS results are for the base flow introduced in §4.3, 3-6, [31]

![Diagram showing transition process](image)

- Crossflow vortices by primary instability (and eventually saturation)
- High-frequency disturbances by secondary instability of (nearly-saturated) vortices
5.2 LSI/Crossflow breakdown, 6 (DNS)

- Steady-crossflow-vortex induced breakdown [31]

\( u_s \)-amplitudes in crosscut with \( \langle u_s \rangle \)

\( \langle u_s \rangle \) and vortex visualization

Transition

\[
\text{low-frequency type-III (z)-mode}
\]

\[
\text{high-frequency type-I (z)-mode}
\]

\[
\operatorname{log}(\max_{y,z}[u_s])
\]

\[
\begin{align*}
\text{steady 3-D} \\
\text{steady 2-D (0,0)} \\
\beta = 160 \\
\beta = 20 \\
t-modal
\end{align*}
\]
5.2 LSI/Crossflow breakdown, 10

- Experimental visualization of (slow) crossflow-vortex induced breakdown on a spinning body of revolution by smoke

\[ U \]

specialty: in the beginning also TS waves can be seen. (Mueller, Nelson, Kegelmann, Morkovin 1981, see [38])
6.1 Laminar Flow Control, DNS, 5

- Example to method B: Passive suppression / delay of crossflow-vortex induced transition in a 3-d boundary layer by forcing of narrow-spaced vortices (UFD/DRE method) with $2/3 \lambda_z$ of the naturally most amplified mode. Note that the $2/3 \lambda_z$ control mode needs to be more amplified initially, and then be damped, i.e. the stability diagram over the $x-\gamma$-plane must have a thumb shape, see §4.3, 5. The control mode is sometimes called ‘subcritical’ referring to its $\lambda_z$ being smaller than the one of the turbulence triggering mode (DNS [31]).
4.5 Literature to §2-§4, 1


4.5 Literature to §2-§4, 2


[22] Luchini, P. 2016 Receptivity to thermal noise of a boundary layer. *AIAA-J.*
6.4 Literature for §5-§6, 1 (see also §4.5)


6.4 Literature for §5-§6, 2 (see also §4.5)


6.4 Literature for §5-§6, 3 (see also §4.5)


6.4 Literature for §5-§6, 4 (see also §4.5)  


