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Boundary Layers, Transition and Separation

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Objectives: Layout key issues,

List potential paths to explore those issues,

Consensus – no-consensus

Informative document for program managers

Many of the issues related to internal flows are also applicable to external flows.

Current understanding of separation and its control is limited.

1. **Effects of roughness in boundary layers** have to be addressed.

   Until adverse pressure gradient effects are understood, roughness will not significantly drive design.

- Mechanisms responsible for separation not understood
  - see Abbot & von Doenhoff for data
- Effects on Zero Pressure Gradient boundary layers (shear stress)
- Effects on separation in pressure gradient (prediction of separation)
- Effect on scalar transport (heat transfer) not understood
- Model for skin friction needed in simulations – first grid point likely to be in buffer layer
- Definition of roughness important for useful experiments
- A lot of validation experiments will be needed.
- How to get to ks for roughness of engineering interest? – depends on wavelength height, etc. for engineering interest?
- Re-discovering the wheel should be avoided: existing knowledge (theoretical and experimental) should find its way into the engineering models. It is a task of the industry to filter out the existing information in the literature for results relevant to its application, being external or internal.

2. Actuators in turbomachinery

- In transition sites and where film cooling hardware exists, active flow control actuators may be useful to enhance turbine performance
- Currently actuators are mainly used in turbomachinery as a tool for understanding flow physics or in special applications. (It is difficult to control 2000-3000 airfoils in a typical machine.) Actuators will have to buy their way onto the engine – must consider overall system cost-to-benefit ratio. (However, a counter example is film cooling is a steady blowing actuator.)
- Control of shock interaction on transonic blades and shock attenuation may be area that could benefit from active flow control.
- Actuators that extend the off-design range of compressors would be important and would be welcome.
- Actuator placement can be guided, today, in arbitrarily complex 2.5-Dimensional flows (inhomogeneous in two-, periodic in the third spatial direction) in the laminar limit, using global instability theory. Effort necessary in order to extend theoretical tools into turbulent flows.

3. Streamwise vortices –

- How do they manage to persist?
- Need the ability to describe, predict, and model their interactions with spanwise vortices
- 2-D base flow instabilities, e.g., cavities and corners (homogeneous in the span- and streamwise spatial direction respectively)
- 3-D base flow instabilities, e.g., on Wygy's 60-deg-swept corrugated shear layer and around turrets of different shapes (semispherical or semispherical attached on cylinders)
- Interpretation of surface flow visualization streaks not clear
    - Time-resolved visualization important to identify nature of streaks.

4. Flow instability modes of laminar separation bubble –

- Reasonably well modeled and understood, but…
- Physics of the separation bubble bursting process and development of turbulence is missing - impact of boundary conditions likely explanation for difficulty but how do we improve this?
- Connection with critical point theory illuminating and should be extended
- How do we extrapolate the laminar instability analysis techniques to turbulent flows?
- Effort to make the analyses of complex separated flows more efficient is necessary.

5. Secondary flows are of primary interest to turbomachinery

- RANS is probably not good enough for modeling turbulent flow in tip regions
  - Bursting of tip vortices needs investigation
  - but how has the wide body of literature on model tip-vortex bursting (Escudier and others, or even earlier) found itself in the design?
- Turbulence and vortex/ shock interaction effects need study
  - Noise generation mechanisms need study
  - Could we identify an academic “unit” problem in order to address this phenomenon?
  - How has the decades-old knowledge on shock/boundary-layer interaction found its way into industrial modeling and design?
- Additional data (possibly DNS on simplified but relevant geometry would be useful
  - Compressor geometry & turbine geometry (cascade?) need to be both attempted as the effects & interactions are different
- Predicting losses associated with these flows or manage them in design process
- Heat transfer is not predicted
  - Heat transfer data on film cooled turbine difficult to obtain - big challenge, needs assistance/support.
- Tip clearance flows is subset of secondary flows
  - Noise correlated with these flows

6. Heat transfer models based on analogy are insufficient

- Good experiments in combination with good numerical results needed to sort out correct physics and develop new models
- Time dependent heat transfer
- Comparing/Leveraging DNS to improve two equation models that are used in industry - very likely to improve state of art. Transition ducts etc - need to collaborate to find data. Thermal field as important as velocity and pressure.

7. Corner flow separation

- Possible benchmark case for joint ("triad") efforts, including experiments, computation and theory. Regarding the latter, global instability analysis of streamwise corner flow can be done today, including pressure gradient. Compressor cascade, turbine cascade, corner in a diffuser are potential benchmark experiments relevant to hub-endwall flow.
- Flow in tip gap may be equally or more important
- Leakage flows around seals – how can they be managed to keep main flow healthy?

8. Transition – transient growth

- Relatively crude correlation-based modeling used in industry – improvement over not having any models. A crude model (SST Mentor & Langtree integrated into CFX code, but not physics based) may be good enough for transition. Interest in unsteady transition, but not likely to significantly influence design. Always looking for more data.
- Correlations being developed, but limited experimental data available, particularly in engines
- Correlations fail near end walls and under off design conditions-
  - More physical based models would be nice
  - Need to identify what are the most essential physics to the problem, even if it means dealing with integral length scales
- Continuously polishing blades believed to lead to better performance – is this true? Why?
- What is the impact that the knowledge on the relation between roughness-induced transition and transient growth has had on modeling? (Rhetorical question, the answer is NONE, at least yet)

9. Experimental design methods

such as those used by chemical engineers may be useful to identify which direction to go in, in order to set priorities

- Use experimental design methods to help make these decisions
- Guidance by theory more than useful
- Dimensional analysis

10. Consensus that experiments and simulations should be coordinated

- 3D separation – start with 2D separation – start sweeping slowly, to assess effects of sweep and difference between 2D and 3D separation
- Separation control to reattach a flow or keep it attached are two separate phenomena – hysteresis like behavior relative to actuator input levels exists
- Dynamic stall on helicopter rotors a different
- Understanding the reasons why RANS simulations fail, and under what conditions they lose validity is important and may benefit from interactions between industry and academia
- Identify limitations in fundamental assumptions that form the basis of turbulence models used by engine companies

11. Massive data bases exist and need to be exploited

- (simulations: DNS of LPTs – Durbin, Fasel, Rodi; and experiments: effects of roughness on transition: White) – have interpretation of these results found their way into modeling and applications? NO! More effort should be applied.