Research strategy for
Stability and transition

Introduction

One of the oldest areas in fluid dynamics is that of stability of laminar flows and the breakdown to turbulence in wall bounded flows. In 1883 Osborne Reynolds performed a famous pipe flow experiment investigating the stability and transition of that flow. Theoretical approaches, which were formulated around 1910, could predict exponential instabilities, but utterly failed for the pipe flow experiment, since no exponential instability exists for that case. Many other flow cases of both fundamental and technical importance have been just as difficult to analyze with the traditional theories of exponential growth of disturbances.

In the 1990's a new research direction paved the way for a better understanding of stability problems where no dominating exponentially unstable disturbances exist. Within our research groups we have pioneered the work on so called transiently or algebraically growing disturbances in boundary layer flows. Mathematically, the non-normality of the linearized operator governing the disturbance growth in a flow, or equivalently the non-orthogonality of the associated eigenfunctions, was the key to analyzing and describing the often large transient growth found in those flows.

Today there is a consensus that such disturbance growth is the main mechanism, which leads to turbulence in boundary layer flows under many practical circumstances, e.g. when the free stream has some finite turbulence level. Figure 1 shows a smoke flow visualization of a boundary layer subject to free stream turbulence. Large-scale numerical experiments performed to study the details of this transition scenario show good agreement with smoke visualizations as well as with more quantitative experimental measurements. The different stages in this

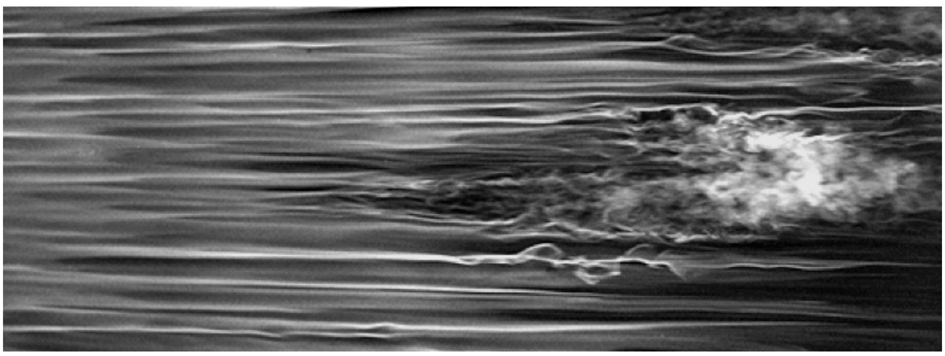

Figure 1: Wind tunnel smoke visualization of transition in a boundary layer subjected to free stream turbulence carried out at KTH. The figure shows the development of streamwise streaks, secondary instabilities and the breakdown to a turbulent spot. The flow is from left to right

scenario have been studied both through optimal disturbance theory, experiments and numerical simulations. Based on these results methods to predict the onset of transition in flows with large free-stream disturbance levels have been developed. Such models have a direct applicability to the problem of transition in turbo-machinery flows where the flow approaching the turbine blades is often highly disturbed.

The future activities within the stability and transition area may be divided into three different branches: receptivity processes and 3D-boundary layers, global modes and complex geometries, and classical stability problems. In 2010 three new PhD projects are starting up dealing with wind turbine applications and are part of a Nordic Consortium on optimization and control of wind power parks. This consortium involves both experimental and numerical activities.

Research environment

A distinguishing mark of the active groups (including here the flow control group with overlapping research interest) is the interplay between theoretical, numerical and experimental research, where similar problems are attacked with different methods. The laboratory resources are excellent and are used by several researchers within the Linné Flow Centre. The Minimum-Turbulence-Level (MTL) wind tunnel, which was inaugurated in 1990, has proven to be a world class resource for advanced transition and stability as well as turbulence research and has made a number of international co-operations possible. A list of people currently involved in transition and stability research, with specific projects, follows (see Table 1). Table 2 lists projects, which have been finalized.

Project titles	PhD.stud. Postdoc	Senior researcher	Proj. Start	Sponsor
Receptivity				
Receptivity analysis in three-dimensional boundary layers	Tempelman	Henningson Hanifi	5/2005	EU-TELFONA
Numerical simulation of receptivity in 3D boundary layers	Schrader	Brandt Henningson	4/2005	VR
Experimental receptivity study of 3D boundary layers	Kurian	Alfredsson Fransson	8/2005	VR, EU-TELFONA, FLOW
Natural transition at low Re-numbers	Shahinfar	Fransson Alfredsson	6/2008	FLOW
Stability in complex geometries				
Experimental investigation of the wake flow instability behind bluff bodies	Fallenius	Fransson Alfredsson	4/2006	VR, GG
Instability of particle laden flows	Klinkenberg	De Lange Brandt	6/2009	VR, KTH, Eindhoven
Wake flow interaction and instability behind wind turbines: experimental	Odemark	Fransson Henningson	2/2010	Energimynd.
Wake flow interaction and instability behind wind turbines: numerical	New	Henningson Fransson	2/2010	Energimynd.
Optimization and control of wind power parks: numerical	New	Henningson Ivanell	2/2010	Vindforsk III
Classical stability problems				
The hydrodynamic stability of a plane liquid jet in a surrounding gas	Tammisola	Söderberg Lundell	6/2006	EU-ECOTARGET, FLOW
Linear mechanisms in rotating turbulent channel flow	Grundestam	Wallin Johansson	2007	VR, KTH
Annular jet instability: experimental	Segalini Örlü	Alfredsson Talamelli	4/2008	Energimynd. KTH
Pattern formation in plane Couette flow turbulence: numerical	Douget	Henningson Schlatter	4/2008	KTH
Experimental and numerical stability study of rotation-induced boundary layers	Imayama	Alfredsson Lingwood	9/2010	KTH

Table 1: Ongoing research activities within FLOW.

Project titles	PhD.stud. Postdoc	Senior researcher	Proj. end	Sponsor
Simulation of wind turbine wakes	Ivanell	Henningson	2009	Vindforsk II
Stability of plane Couette flow in the rotating framework: experiments	Tsukahara	Alfredsson Tillmark	10/2005	KTH
Numerical simulations of pipe flow	Åsén	Kreiss	2007	VR

Table 2: Finished projects within FLOW.

Overall Research Goals

The future direction in the area of stability and transition of fluid flows is towards enhanced physical understanding of the receptivity mechanisms, stability in complex geometries and further understanding of classical stability problems. Expected long-term breakthroughs within the stability and transition area are:

- To develop accurate direct numerical simulations methods, coupled with Krylov subspace and Arnoldi techniques, in order to attack the stability of truly complex flows.
- To use optimal disturbance growth analysis based on, for instance, the global modes to obtain understanding of the disturbance development in complex flows, e.g. the instability developments and sound generation.
- To create a new experimental database, of different receptivity mechanisms, forming the base of future transition prediction models.
- To experimentally map out the structure formation and wake flow instability behind rectangular based fore-bodies using high speed stereo Particle Image Velocimetry.
- To take a further step towards solving the classical stability problems, which have been puzzling researchers for many years.

Roadmap

Receptivity. Boundary layer disturbance receptivity is an area where we both have experimental and numerical activities. The geometries adopted here are plane leading edge and swept leading edge with the possibility to vary the external pressure gradient in order to simulate cross flow instabilities in 3D boundary layers. The short-term goals in this area are:

- To gain knowledge in experimental roughness implementation techniques as well as three component hot-wire probes,
- To establish receptivity coefficients for both surface roughness and free stream turbulence affects on 3D boundary layers, both experimentally and numerically,
- To apply adjoint modes in surface roughness receptivity, which will give direct information on where and how external disturbances can be expected to enter into a boundary layer,
- To experimentally investigate the correlation between free stream turbulence characteristics to boundary layer transition.

In this area we have international and national collaborations with Dr. Casalis at ONERA in Touluse, and Dr. Zaki, Imperial College.

Stability in complex geometries. A new direction of stability research is the investigation of stability of flows in complex geometries using both experiments and DNS. For example, an optimal superposition of global modes can often reveal more complex disturbance behaviour than single eigenmodes, e.g. large transient growth of wave-packets and great sensitivity to forcing. A large activity within FLOW will be in the area of wind turbine wakes. The focus is on wake interaction and tip-vortex breakdown. The short-term goals of the stability in complex geometries area are:

- To study the disturbance behaviour in complex 3D flows by using a global mode approach. Of particular interest is the hydrodynamic stability of a jet in cross-flow. Other flows of interest are separated flows and three-dimensional modes in boundary layers.
- To develop methods for direct numerical simulation of transitional flows in complex geometries
- To experimentally investigate the wake flow instability and structure formations behind a rectangular based fore-body and annular jet instability
- To experimentally and numerically study the tip-vortex breakdown generated by wind turbine rotor blades and the wind turbine wake interactions.

International co-workers in global modes and complex geometries are Prof. De Lange at Eindhoven, Prof. Schmid at LadHyX, Ecole Polytechnique and Prof. Sørensen, Technical University of Denmark, Dr. Fischer, Argonne National Lab, and Prof. Juniper, Cambridge University, Dr. Mavriplis, Univ. of Ottowa.

Classical stability problems. Both the plane Couette and the Hagen-Poiseuille are linearly stable flows when analyzed using the classical modal theory. The stability and transition characteristics of the Couette flow are being studied both numerically and experimentally. Absolute instability investigations on a rotating disc/cone and plane jets are other classical stability problems. The short-term goals in this area are:

- To perform PIV and LDV measurements to study plane Couette flow both in the rotating and non-rotating frameworks.
- To search for recurrence pattern formations in low Re-number Couette flow turbulence
- To study the hydrodynamic stability of a plane liquid jet in a surrounding gas
- To investigate the instability of the rotation-induced boundary layers.

In this area we have international collaborations with Prof. Matsubara from Shinshu University in Nagano, Dr. Cossu, IMFT Toulouse, Dr. Douget, LIMSI, Paris, Dr. Garret, Univ. of Leister.