Proceedings of
Office of Naval Research Award Number N00014-99-1-0966

IUTAM SYMPOSIUM "LAMINAR-TURBULENT TRANSITION"

1 AUGUST 1999 – 31 DECEMBER 1999

To

Office of Naval Research
Program Officer Candace Wark ONR
Code: 333
Ballston Tower One
800 North Quincy Street
Arlington, VA. 22217-5660

By

William S. Saric
Professor, Vice Chair Aerospace Engineering

Mechanical and Aerospace Engineering
Arizona State University
Box 87-6106
Tempe, AZ. 85287-6106

June 2000

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

[Stamp: DESI QUALITY INSPECTED A]

[Stamp: 20000615 017]
Preface

The origins of turbulent flow and the transition from laminar to turbulent flow are among the most important unsolved problems of fluid mechanics and aerodynamics. Besides being a fundamental question of fluid mechanics, there are any number of applications for information regarding transition location and the details of the subsequent turbulent flow.

The IUTAM Symposium on Laminar-Turbulent Transition, co-hosted by Arizona State University and the University of Arizona, was held in Sedona Arizona. Although four previous IUTAM Symposia bear the same appellation (Stuttgart 1979, Novosibirsk 1984, Toulouse 1989, and Sendai 1994) the topics that were emphasized were each different and reflect the evolving nature of our understanding of the transition process.

The major contributions of Stuttgart 1979 centered on nonlinear behavior and later stages of transition in two-dimensional boundary layers. Stability of closed systems was also included with Taylor vortices in different geometries. The topics of Novosibirsk 1984 shifted to resonant wave interactions and secondary instabilities in boundary layers. Pipe- and channel-flow transition were discussed as model problems for the boundary layer. Free shear layers were discussed and a heavy dose of supersonic papers appeared for the first time. The character of Toulouse 1989 was also different in that 3-D boundary layers, numerical simulations, streamwise vortices, and foundation papers on receptivity were presented. Sendai 1994 saw a number of papers on swept wings and 3-D boundary layers. Numerical simulations attacked a broader range of problems.

The Sedona 1999 meeting was almost exclusively bounded shear layers as open systems. The major impact topics were receptivity of initial disturbances, crossflow instabilities, supersonic flows, and control of transition. More papers appeared on combined numerical and experimental work. In other cases, teams from different institutes combined resources to solve complicated problems. The objectives of many of these studies were to properly define the fundamental physics of the stability and transition process. One can track certain freestream disturbances that provide the initial conditions for unstable waves in somewhat complicated geometries. As a consequence, this fundamental knowledge now enables different techniques of transition control and its subsequent decrease in drag. One expects increased emphasis on this topic. Papers on transient growth and sub-critical development of 3-D disturbances pointed to future areas of research.

**Countries represented and number of participants**

<table>
<thead>
<tr>
<th>Country</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>1</td>
</tr>
<tr>
<td>Brazil</td>
<td>1</td>
</tr>
<tr>
<td>Canada</td>
<td>2</td>
</tr>
<tr>
<td>China</td>
<td>2</td>
</tr>
<tr>
<td>France</td>
<td>7</td>
</tr>
<tr>
<td>Germany</td>
<td>24</td>
</tr>
<tr>
<td>Greece</td>
<td>1</td>
</tr>
<tr>
<td>India</td>
<td>2</td>
</tr>
<tr>
<td>Israel</td>
<td>1</td>
</tr>
<tr>
<td>Italy</td>
<td>1</td>
</tr>
<tr>
<td>Japan</td>
<td>15</td>
</tr>
<tr>
<td>Russia</td>
<td>11</td>
</tr>
<tr>
<td>Sweden</td>
<td>2</td>
</tr>
<tr>
<td>Switzerland</td>
<td>3</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>1</td>
</tr>
<tr>
<td>U.K.</td>
<td>16</td>
</tr>
<tr>
<td>Ukraine</td>
<td>1</td>
</tr>
<tr>
<td>USA</td>
<td>42</td>
</tr>
</tbody>
</table>

Total participants: 132
Symposium Sponsors
International Union of Theoretical and Applied Mechanics (IUTAM)
Arizona State University
University of Arizona
ASU Unsteady Wind Tunnel
UA Computational Fluid Dynamics Laboratory
Army Research Office
Office of Naval Research
National Science Foundation
Air Force Office of Scientific Research.

Scientific Committee
W. Saric (Co-Chair) (USA)  V. Koslov (Russia)
H. Fasel (Co-Chair) (USA)  V. Levchenko (Russia)
D. Arnal (France)           R. Narasimha (India)
P. Baines (Australia)       T. Tatsumi (Japan)
H. Bippes (Germany)         J. van Ingen (Netherlands)
M. Gaster (UK)              H. Zhou (China)
R. Kobayashi (Japan)

Local Organizing Committee
H. Fasel (UA)               E. Reshotko (CWRU)
E. Kerschen (UA)            W. Saric (ASU)
H. Reed (ASU)               I. Wygnanski (UA)

Support Personnel
Colleen Leatherman (ASU)    Jürgen Seidel (UA)
Brandon Latek (ASU)         Dominic vonTerzi (UA)
Mark Linnick (UA)           Stefan Wenz (UA)
Jarmo Mönttinen, (ASU)      Edward White (ASU)
Richard Sandberg (UA)       Hui-Liu Zhang (UA)
Sunday 12 September
1800 - 2200  Reception and Registration at Poco Diablo Resort-Sedona, AZ.
(located in the Conference-Center)

Monday 13 September
0700 - 0845  Registration and continental breakfast
(Registration at the Conference-Center/continental breakfast on lower patio)
0845 - 0900  OPENING REMARKS
KEYNOTE LECTURES
Chairman: M. Gaster
0900 - 0920  T. Tatsumi
Turbulence in the turn of the century
0920 - 1005  L. Mack
Early history of compressible linear stability theory
1005 - 1030  BREAK
(coffee, tea, water served in hallway)

SESSION A: RECEPTIVITY I
Chairman: V. Kozlov
1030 - 1050  P. Hammerton, E. Kerschen
Effect of leading-edge geometry and aerodynamic loading on receptivity to acoustic disturbances
1050 - 1110  L.M. Cullen, H.P. Horton
Acoustic receptivity in boundary layers with surface roughness
1110 - 1130  N. Peake, R. Lingwood
A casual stability analysis of the boundary-layer flow over a compliant wall
1130 - 1150  C. Airlau, S. Walther, A. Bottaro
Nonparallel receptivity and the adjoint PSE
1150 - 1340  LUNCH
(lunch served on the lower patio/Mexican Fajita Buffet)

SESSION B: RECEPTIVITY II
Chairman: V. Levchenko
1340 - 1400  Y. Kachanov
Three-dimensional receptivity of boundary layers to external perturbations
1400 - 1420  J. Wandelby, T. Corke
Boundary-layer receptivity to freestream sound on elliptic leading edges of flat plates
1420 - 1440  R. King, K. Breuer
Non-localized acoustic receptivity and subsequent disturbance growth in a Blasius boundary layer
1440 - 1500  D.G. Lassaigne, W.O. Criminale, R.D. Joslin, T.L. Jackson
Receptivity and bypass dynamics
1500 - 1520  W. Wurz, W. Herr, A. Worner, U. Rist, S. Wagner, Y. Kachanov
Study of 3-D wall roughness acoustic receptivity on an airfoil
1520 - 1540  V. Kosorygin
Experiments on receptivity, stability, and transition of 2-D laminar boundary layers with streamwise pressure gradients
1540 - 1600  E. White, W. Saric, R. Radetzky Jr.
Leading-edge acoustic receptivity measurements using a pulsed-sound technique
1600 - 1630  BREAK AND POSTER SESSION SET UP
(coffee, teas, assorted soft drinks, water served in the hallway)
POSTER SESSION I (MONDAY AND TUESDAY)

1.1 S. Collis, A. Dobrinsky
Evaluation of adjoint based methods for the prediction of receptivity

1.2 Y. Su, T. Herbert
Receptivity to freestream turbulence and the effect of longitudinal vortices in boundary-layer transition

1.3 D. Nichols, P. Hammerton
Receptivity for a flat plate with a rounded leading edge

1.4 H. Grek, V. Kozlov, D. Sboev
Experiments on the receptivity of a boundary layer to a localized freestream disturbance

1.5 M. Ustinov, M. Kogan, V. Shumilkin, S. Zhigulev
Experimental study of flat-plate boundary layer receptivity to vorticity normal to leading edge

1.6 M. Katasonov, V. Kozlov
Boundary-layer longitudinal localized structures control by means of spanwise wall oscillations

1.7 C. Gmelin, U. Rist, S. Wagner
DNS of active control of disturbances in a Blasius boundary layer

1.8 M. Baumann, D. Sturzebecher, W. Nitsche
Active control of T-S instabilities on an unswept wing

1.9 A. Bakchunov, M. Katasonov, P. Alfredsson, V. Kozlov
Control of streaky structures by localized blowing and suction

Late-stage transitional boundary-layer structures. Direct numerical simulation and experiment

1.11 G. Grek, M. Katasonov, V. Kozlov, Y. Chernoray
Experimental study of a lambda-structure development and mechanism: Its transformation into the turbulent spot

1.12 S. Houten, J. Healey, C. Davies
Nonlinear evolution of Tollmien-Schlichting waves at finite Reynolds numbers

1.13 J. Healey
On why oblique waves in the Blasius boundary layer show stronger nonparallel effects than planar waves

1.14 R. Govindarajan, N. Narasimha
Stability of weakly nonsimilar swept-wing boundary layers

1.15 P. Taniguchi, F. Browand, R. Blackwelder
Boundary-layer transition due to the entry of a small particle

1.16 Y. Kohama, P. Alfredsson, Y. Egami, M. Kawakami
Turbulent energy production mechanism in general boundary-layer transition

1.17 S. Reddy, P. Ioannou
Energy transfer analysis of turbulent plane Couette flow

1.18 P. Hall
Nonlinear initial value problems for wave/vortex interactions in channel flows

1.19 S. Wernz, H. Fasel
Numerical investigation of resonance phenomena in wall-jet transition

1.20 S. Gaponov, B. Smorodsky
Supersonic boundary-layer receptivity to streamwise acoustic field

1.21 F. Lundell, P. Alfredsson
Feed-forward control of streak instabilities in plane Poiseuille flow by localized suction

1.22 R. Melling, M. Kloker
Effect of suction through arrays of holes on a 3-D boundary layer investigated by spatial direct numerical simulation

Tuesday 14 September

0700 - 0820 Registration and continental breakfast
(Registration at the Conference-Center/continental breakfast on lower patio)

SESSION C: ATTACHMENT LINE AND GENERAL TOPICS
Chairman: R. Kobayashi
0820 - 0840  R. Mukund, P. Viswanath, J. Crouch
Relaminarization and retransition of accelerated turbulent boundary layers on a convex surface

0840 - 0900  A. Dietz, C. Coleman, J. Laub, D. Poll
Effect of wall temperature on roughness induced attachment-line transition

0900 - 0920  S. Seddougui, B. Orme
Nonlinear Instability of Hypersonic Flow over a cone

0920 - 0940  M. Gaster
On the growth of waves in boundary layers

0940 - 1020  BREAK
(coffee, tea, water served in hallway)

SESSION D: 3-D TRANSITION IN 2-D FLOWS
Chairman: D. Arnal

1020 - 1040  S. Bake, H. Fernholz
The formation of secondary structures and random perturbations in the development of periodic Lambda structures in a laminar boundary layer

1040 - 1100  M. Asal, M. Minagawa, M. Nishioka
Instability and breakdown of the three-dimensional high-shear layer associated with a near-wall low-speed streak

1100 - 1120  R. Bowles
On vortex interaction in the later stages of boundary-layer transition

1120 - 1140  E. Malkiel, V. Levinson, M. Rosenfeld, J. Cohen
The evolution of hairpin vortices in shear flows

1140 - 1200  M. Mederlos, M. Mendonca
Nonlinear three-dimensional wavetrains of small amplitude in boundary layers: experiments, theory and computations

1200 - 1220  V. Kozlov, G. Grek
Stationary and nonstationary streaky structures and secondary instability of boundary layers

1220 - 1340  LUNCH
(lunch served on lower patio/Hot Dog, Burger Buffet)

SESSION E: CONTROL
Chairman: R. Narasimha

1340 - 1400  Y. Fukunishi, I. Ebina, R. Kobayashi
Generation of oblique waves in a Blasius boundary layer by thin Piezo-film actuators attached to the wall surface

1400 - 1420  P. Cathalfau, P. Luchini
Optimal control by blowing and suction at the wall of algebraically growing boundary-layer disturbances

1420 - 1440  C. Davies, P. Carpenter, D. Lockerby
A novel velocity-vorticity method for simulating boundary-layer disturbance evolution and control

1440 - 1500  P. Andersson, M. Berggren, D. Henningsson
Optimal three-dimensional perturbations in the Blasius boundary layer

1500 - 1520  N. Yurchenko, J. Delfs
Optimal control of boundary layers under body forces

1520 - 1720  BREAK AND POSTER SESSION SET UP
(coffee, teas, assorted soft drinks, water served in the hallway)

1720 - 1750  Poster session break down

1900 - 2130  BANQUET
(located in the conference center building)

Wednesday 15 September

0630 - 0730  continental breakfast served on lower patio
0715-0730  board buses for Grand Canyon-main entrance

0715 - 1730  GRAND CANYON TOUR
Thursday 16 September

0700 - 0800  Registration and continental breakfast
(Registration at the Conference-Center/continental breakfast on lower patio)

SESSION F: GENERAL TOPICS
Chairman: H. Zhou
0820 - 0840  S. Becker, K. Condle, C. Stoots, D. McEligot
Reynolds-stress development in the viscous layer of a transitional boundary layer
0840 - 0900  J. Watomuck
Distortion of Tollmien-Schlichting waves by leading-edge vortices
0900 - 0920  P. MoreSCO, J. Healey
Convective and absolute instability in the mixed convection boundary layer over a vertical flat plate
0920 - 0940  A. Cabal, J. Szumbarski, J. Fioryan,
Stability of Poiseuille flow in a corrugated channel
0940 - 1000  R. Govindarajan, R. Narasimha
The transition zone on a heated axisymmetric body
1000 - 1030  BREAK
(coffee, tea, water served in hallway)
SESSION F: GENERAL TOPICS CONTINUED
Chairman: J. van Ingen
1030 - 1050  G. Walker, J. Hughes
The occurrence of natural transition phenomena in periodic transition on axial compressor blades
1050 - 1110  J.P. Gostelow, H.P. Hodson, G.J. Walker
Comparisons between triggered turbulent spots and unsteady transition phenomena on compressor and turbine blading
1110 - 1130  M. Matsubara, A. Bachinov, J. Fransson, P. Alfredsson
Growth and breakdown of streaky structures in boundary layer transition induced by freestream turbulence
1130 - 1150  A. Tumin
Onset of turbulence in circular pipe flows
1150 - 1210  J. Reuter, D. Rempfer
A hybrid spectral/finite-difference scheme for the simulation of pipe-flow transition
1210 - 1320  LUNCH
(lunch served on lower patio / Chef's Deli Buffet)

SESSION G: SUPersonic
Chairman: H. Fasel
1320 - 1340  S. Gaponov
Transition of supersonic boundary layers (experiment and theory review)
1340 - 1400  C. Mielke, L. Kleiser
Investigation of transition to turbulence in a 3-D supersonic boundary layer
1400 - 1420  E. Reshotko, A. Tumin
The blunt body paradox: A case for transient growth
1420 - 1440  M. Malik
1440 - 1500  A. Fezer, M. Kloker  
Spatial direct numerical simulation of transition phenomena in supersonic flat-plate boundary layers

1500 - 1530  BREAK  
(coffee, teas, assorted soft drinks, water served in the hallway)

1530 - 1550  A. Maslov, S. Mironov  
Experimental investigations of the hypersonic boundary-layer stability

1550 - 1610  S. Schneider  
Development of a Mach-6 quiet-flow Ludwig tube for transition research

1610 - 1630  X. Yuan, H. Zhou  
A numerical study for a small amplitude T-S wave in a supersonic boundary layer

1650 - 1710  BREAK AND POSTER SESSION SET UP  
(coffee, teas, assorted soft drinks, water served in the hallway)

1710 - 1910  POSTER SESSION II (THURSDAY AND FRIDAY)

2.1  X. Zhong  
DNS of boundary-layer receptivity to freestream sound for hypersonic flows over blunt elliptical cones

2.2  N. Semionov, A. Kosinov  
Experimental study of supersonic boundary-layer receptivity in controlled conditions

2.3  V. Lysenko, A. Kosinov, Y. Yermolaev  
Development of artificial disturbances in the boundary layer on a plate and in the wake behind it at supersonic free-flow speed

2.4  A. Kosinov, Y. Yermolaev, N. Semionov  
On anomalous wave processes in supersonic boundary layer

2.5  A. Karabis, S. Shaw, V. Theofilis  
On the inviscid spatial instability of supersonic boundary-layer flow along bodies of revolution

2.6  D. Bointun, A. Sheplyuk, A. Sidorenko  
Experimental investigations of disturbance development in the hypersonic boundary layer on a conical model

2.7  S. Sakaue, M. Asai, M. Nishikata  
On the receptivity process of supersonic laminar boundary layer

2.8  D. Mitra, R. Seshadri, K. Rao, R. Govindarajan  
Low-order stability theory for non-parallel compressible boundary layer flow

2.9  A. Kosinov, Y. Yermolaev, N. Semionov  
On correspondence of laminar-turbulent transition processes at natural and controlled supersonic experiments on flat plate

2.10  C. Stemmer, M. Kloker  
Later stages of transition of an airfoil boundary layer flow excited by a harmonic point source

2.11  L. Schouveiler, P. LeGal, M.P. Chauve  
Experiments on the transition to turbulence of the flow between a stationary and a rotating disk

2.12  M. Högberg, D. Henningson  
Secondary instability of crossflow vortices in Falkner-Skan-Cooke boundary layers

2.13  C. Cossu, J. Chomaz, M. Costa  
Maximum growth of Görtler vortices

2.14  P. Ardonceau, D. Aymer de la Chevalerie  
Non-normality of the Görtler operator and spatial amplification

2.15  L. Girgis, J. Liu  
Linear stability of the supersonic turbulent boundary layer to Görtler vortices on a concave wall

2.16  C. Whang, X. Zhong  
Direct numerical simulation of Görtler instability in hypersonic boundary layers

2.17  F. Bahri, Y. Kohama, J. Iino and Aota  
Effect of the pressure gradients on the secondary instability of Görtler flow

2.18  H. Stuer, A. Gyr, W. Kinzelbach
Laminar-turbulent transition of a separation flow on a forward facing step
2.19 A. Dovgal
Flow instability in laminar separation bubbles
2.20 R. Lingwood, P. Alfredsson
Experimental study of the stability of the Bödewadt layer
2.21 G. Han, A. Tumin, I. Wygnanski
Late stage of transition in a circular pipe flow
2.22 P. Wassermann, M. Klocker
DNS investigations of the development and control of crossflow vortices in a 3-D boundary layer flow
2.23 Y. Kachanov, D. Koptsev, B. Smorodsky
3-D stability and receptivity of 2-D self-similar boundary layer with adverse pressure gradient
2.24 E. Reshotko, M. Vargas, H. Reed
Relation of glaze ice formations on swept wings to crossflow instability
2.25 T. Wintergerste, L. Kleiser
Secondary stability analysis of nonlinear crossflow vortices

Friday 17 September

0700 - 0800  Registration and continental breakfast
(Registration at the Conference-Center/continental breakfast on lower patio)

SESSION H: CROSSFLOW
Chairman: E. Kerschen

0800 - 0820  D. Arnaud, A. Seradjie, J. Archambaut
Influence of surface roughness and suction on the receptivity of a swept wing boundary layer

0820 - 0840  T. Herbert
Stability and transition in 3-D boundary layers

0840 - 0900  W. Koch
Absolute/convective instability analysis of secondary crossflow vortices in a 3-D boundary layer

0900 - 0920  C. Abegg, H. Bippes, E. Janke
Stabilization of boundary-layer flows subject to crossflow instability with the aid of suction

0920 - 0940  Y. Yokokawa, Y. Fukunishi, N. Itoh
Numerical study of excitation of two different instabilities in e-D boundary layer on a yawed cylinder

0940 - 1000  G. Bonfigli, M. Klocker
Three-dimensional boundary-layer transition phenomena investigated by spatial indirect numerical simulation

1000 - 1030  BREAK
(coffee, tea, water served in hallway)

1030 - 1050  F. Bertolotti
On the connection between crossflow vortices and attachment-line instabilities

1050 - 1110  J.S. Luo, H. Zhou
A theoretical investigation of the development of the stationary crossflow vortices in the boundary layer on a swept wing

1110 - 1130  V. Levchenko, V. Scherbakov
Experimental study of traveling waves in 3-D boundary layer on a swept wing

1130 - 1150  S. Takagi, N. Itoh, N. Tokugawa
Characteristic features of traveling disturbances originating from a point source on a rotating-disk

1150 - 1210  N. Itoh
Multimode instability of the 3-D boundary layer along an infinite attachment line

1210 - 1340  LUNCH
(lunch served on lower patio/East meets West Buffet)

SESSION I: WALL JETS AND SEPARATION
Chairman: E. Reshotko
1340 - 1400  J. Seldel, H. Fasel
Numerical investigation of the heat transfer mechanisms in wall-jet transition

1400 - 1420  U. Maucher, U. Rist, S. Wagner
Secondary disturbance amplification and transition in laminar separation bubbles

1420 - 1440  V. Theofilis
Global linear instabilities in laminar separated boundary layer flow

1440 - 1500  B. Wang, D. Boducki, L. Redekopp,
Transition in separated flows via global instability

1500 - 1520  A. Dovgal, A. Boiko
Effect of harmonic excitation on instability of laminar separation bubble on an airfoil

1520 - 1540  S. Hein
Linear and nonlinear nonlocal instability analyses for two-dimensional laminar separation bubbles

1540 - 1550  Closing Remarks

1550 - 1620  BREAK AND POSTER SESSION SET UP
(coffee, teas, assorted soft drinks, water served in the hallway)

1620 - 1840  POSTER SESSION II CONTINUED

1840 - 1910  Poster session breakdown
The IUTAM Symposium on Laminar-Turbulent Transition, co-hosted by Arizona State University and the University of Arizona, was held in Sedona, Arizona. Although four previous IUTAM Symposia bear the same appellation (Stuttgart 1979, Novosibirsk 1984, Toulouse 1989, and Sendai 1994) the topics that were emphasized were each different and reflect the evolving nature of our understanding of the transition process.

The Sedona 1999 meeting was almost exclusively bounded shear layers as open systems. The major impact topics were receptivity of initial disturbances, crossflow instabilities, supersonic flows, and control of transition. More papers appeared on combined numerical and experimental work. In other cases, teams from different institutes combined resources to solve complicated problems. The objectives of many of these studies were to properly define the fundamental physics of the stability and transition process. One can track certain freestream disturbances that provide the initial conditions for unstable waves in somewhat complicated geometries. As a consequence, this fundamental knowledge now enables different techniques of transition control and its subsequent decrease in drag. One expects increased emphasis on this topic. Papers on transient growth and sub-critical development of 3-D disturbances pointed to future areas of research.