NASA/CP—2010-216612

UNIVERSIDAD POLITÉCNICA DE MADRID

E.T.S. de Ingenieros Aeronáuticos

GLOBAL INSTABILITY OF LAMINAR SEPARATION BUBBLES

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Ph.D. Student: Daniel Rodriguez

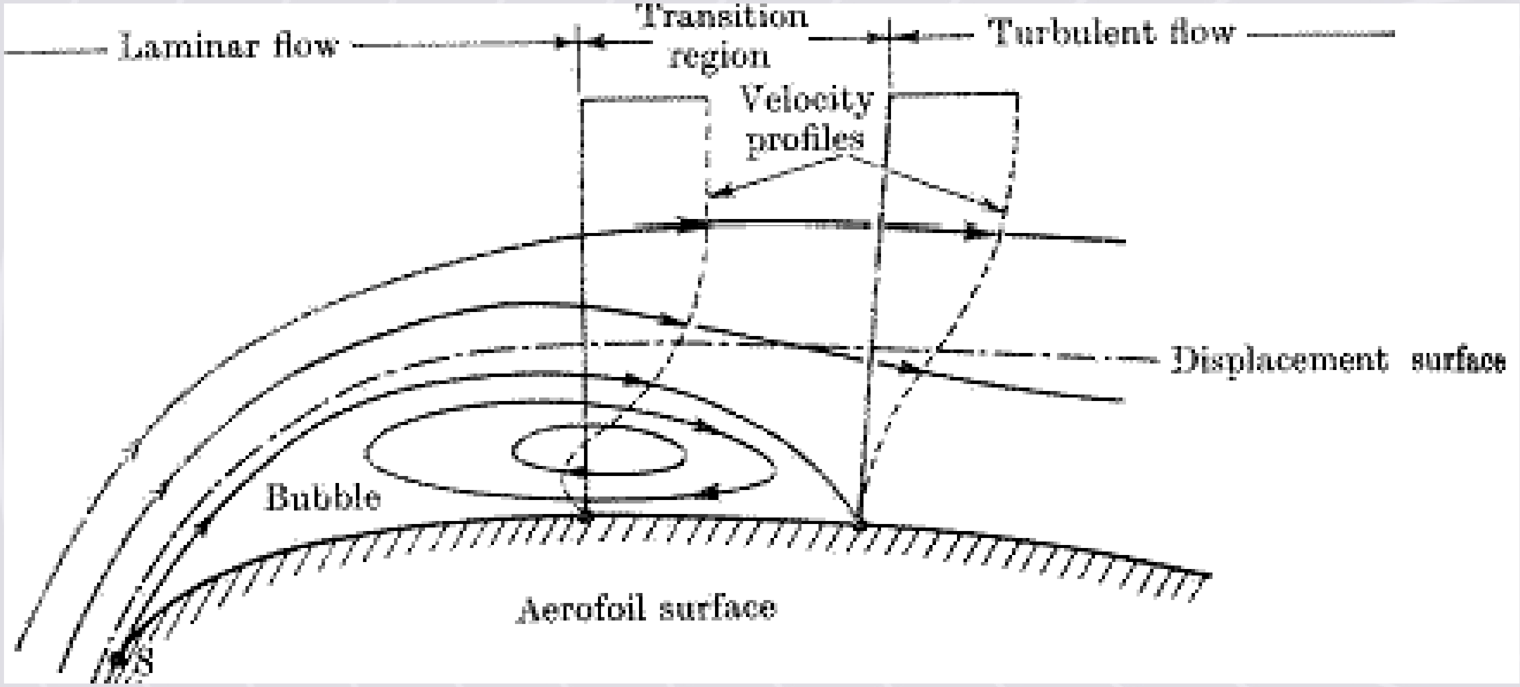
PM: Douglas Smith

AFOSR Grant: FA8655-06-1-3066

Introduction and Background

COMMON WISDOM ON LSB

- Separation under adverse pressure gradient
- Reversed flow region enclosed ➔ Shear layer
- Kelvin-Helmholtz instability ➔ transition to turbulence
- Turbulent strong mixing forces re-attachment



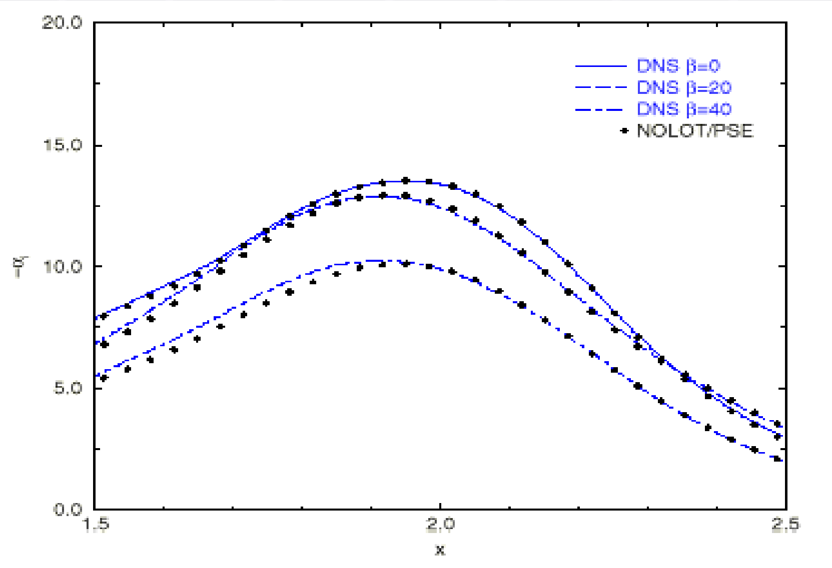
(Horton 1968)

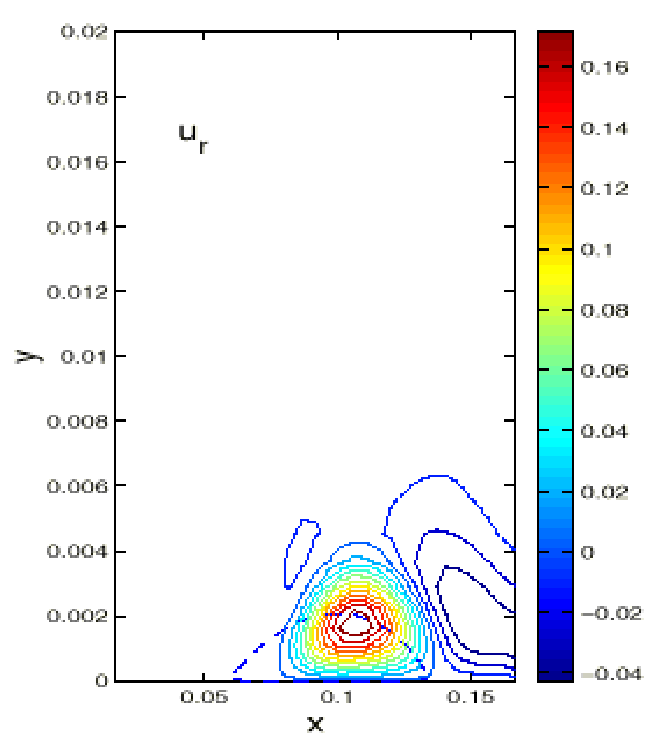
A MORE RECENT VIEW

- **Two** **different classes** **of eigenmodes:**

Shear-layer/KH

Global mode

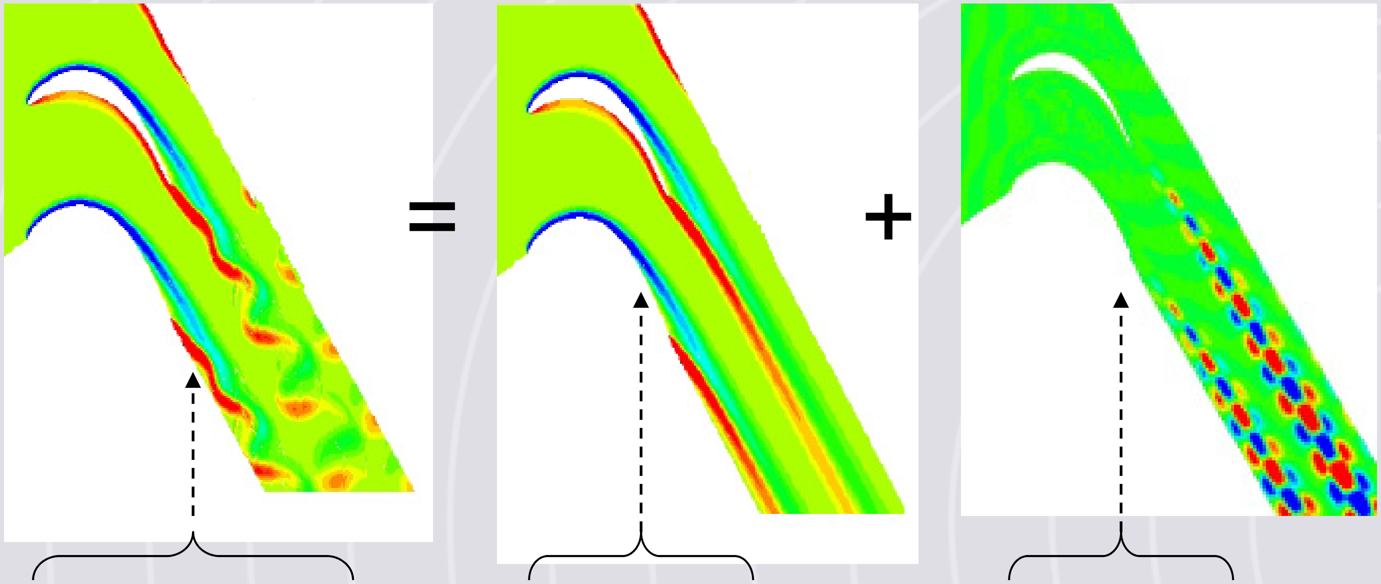




Th, Hein & Dallmann Phil. Trans. R. Soc. Lond. A (2000) 358: 3229-3246

LPT FLOWS – THE (SL) WAKE MODE

- **Amplification of the wake mode gives rise to the 2D time-periodic basic state**

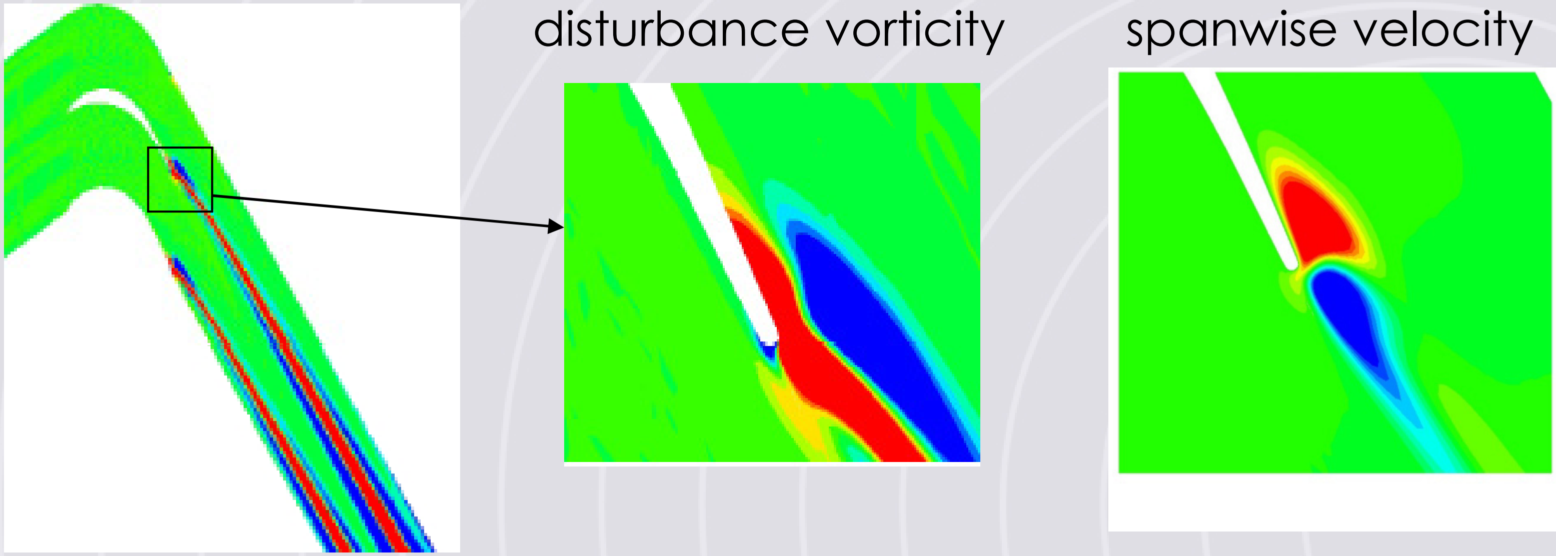


$$\mathrm{q}(x,y,t) = \bar{\mathrm{q}}(x,y) + \varepsilon\ \hat{\mathrm{q}}(x,y)\,\mathrm{exp}\,\ominus$$

Abdessemed, Sherwin, Th, JFM (2009) 628: 57-83

LPT FLOWS – THE BUBBLE MODE

**The bubble mode is
stronger damped than the wake mode is**



disturbance vorticity

spanwise velocity

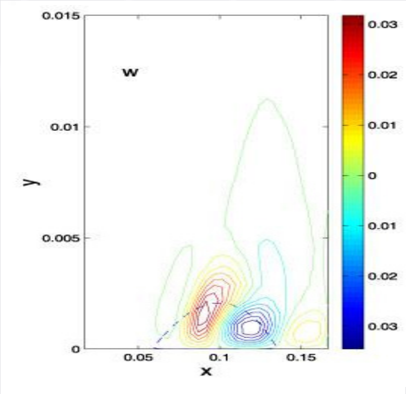
Abdessemed, Sherwin, Th, JFM (2009) 628: 57-83

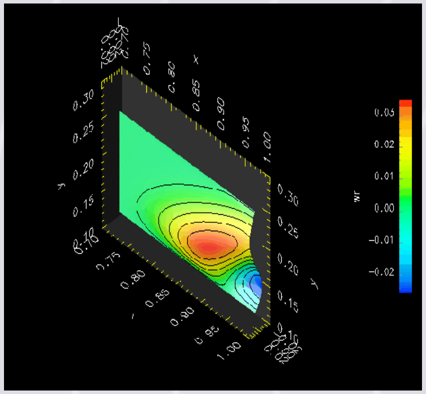
A UNIFYING PERSPECTIVE

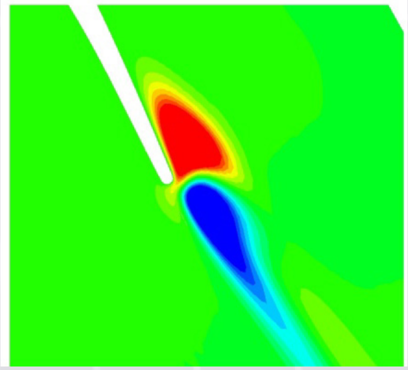
THE GLOBAL MODE OF LSB

- **The struture of the amplitude functions of the minimally damped global eigenmode of the LPT blade…**

spanwise w(x,y)







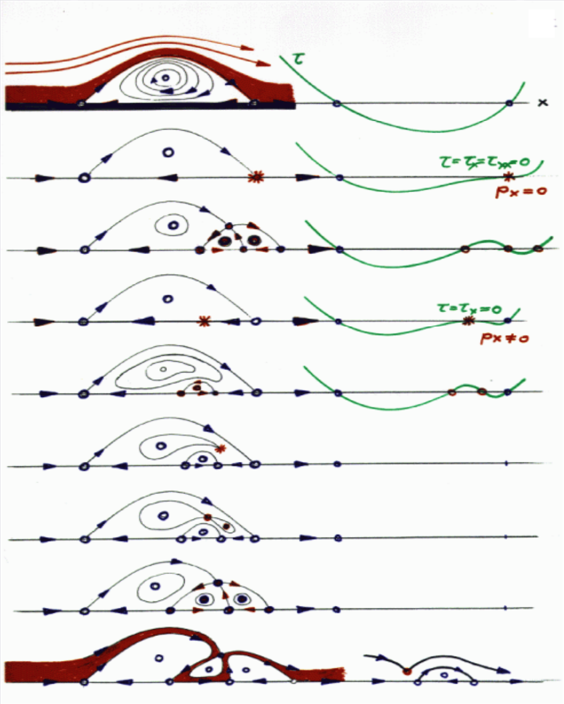
…is analogous to that on the flat-plate and the NACA 0012 aerofoil

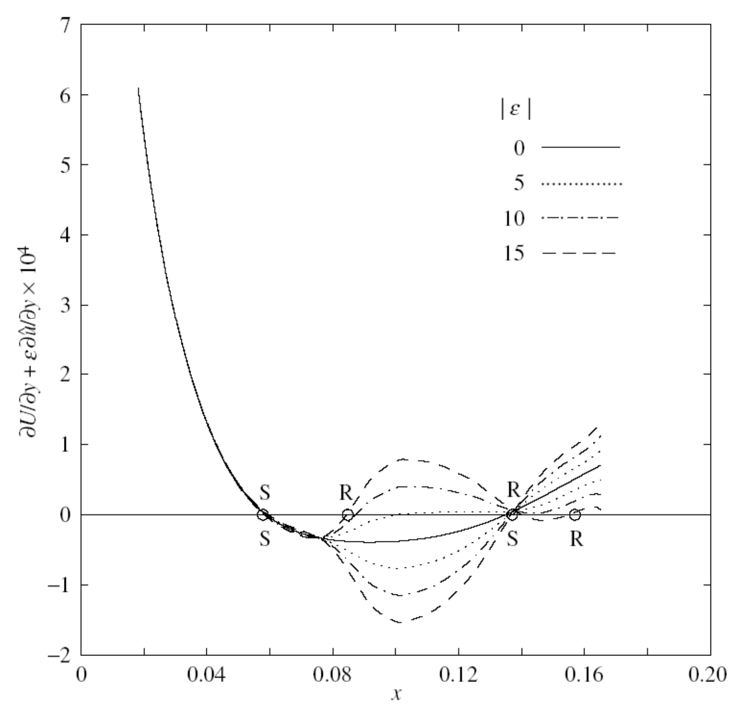
GLOBAL INSTABILITY OF LSB

Configuration	Authors	Methodology
Airfoils	Gaster (1964)	-
APG flat plate BL	Hammond & Redekopp (1998)	Absolute/Convective instability analysis
-//-	Theofilis (1998, 1999) Theofilis, Hein & Dallmann (2000)	BiGlobal instability analysis
Backward- and forward-facing steps	Barkley, Gomes, Henderson (2001) Marquet et al. (2006) Marino & Luchini (2009)	BiGlobal instability analysis, DNS
Low Pressure Turbine blades	Abdessemed, Sherwin & Theofilis (2004; 2006; 2009)	BiGlobal analysis, DNS
Shock / Boundary-Layer Interaction	Boin, Robinet (2004; 2007)	BiGlobal instability analysis, DNS
NACA Airfoils at AoA	Theofilis, Barkley & Sherwin (2002) Crouch et al. (2007; 2009)	BiGlobal instability analysis, DNS
Rounded open cavity, S-shaped duct	Hoepffner et al. (2007), Akervik et al. (2007), Marquet et al. (2008)	BiGlobal instability analysis, DNS
Bump-induced separation	Ehrenstein et al. (2007)	BiGlobal instability analysis, DNS
Low Pressure Turbine Cascade	Brear & Hodson (2004)	Experiment
Iced Airfoil	Jacobs & Bragg (2006)	Experiment

GLOBAL INSTABILITY & FLOW TOPOLOGY – 1998

- **Dallmann’s conjecture on the topological flowfield changes due to the global mode**

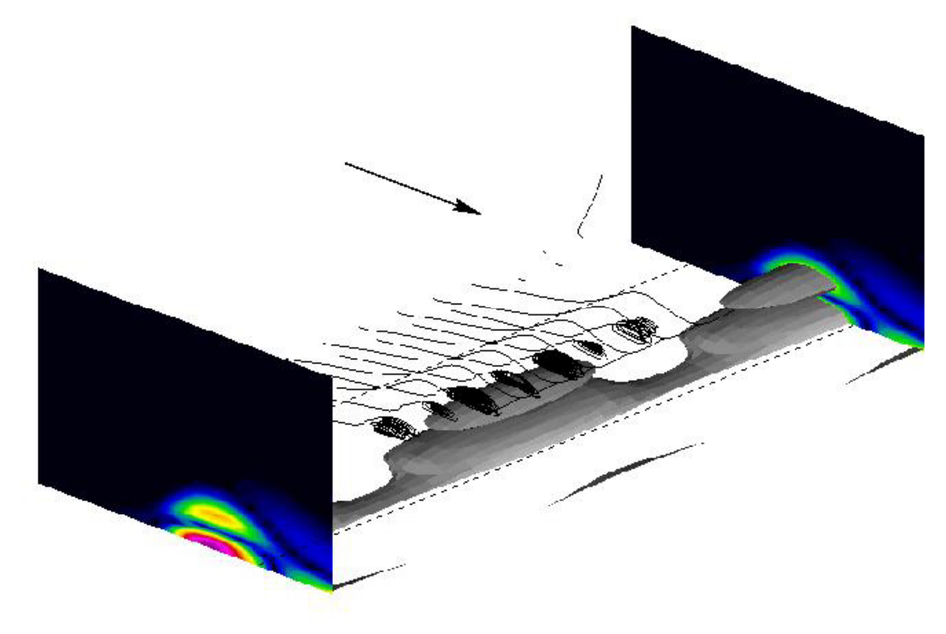




Th, Hein & Dallmann Phil. Trans. R. Soc. Lond. A (2000) 358: 3229-3246

GLOBAL INSTABILITY & FLOW TOPOLOGY – 1999

- **Amplification of the global mode leads to three-dimensionalization of the primary reattachment line in 3d…**



…while it leaves the primary separation line unaffected

Th, IUTAM Laminar-turbulent transition V, Sedona (1999) 663-668

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The present contributions

OUTLINE

Incompressible Flow

- Some numerics on the direct/adjoint EVP
- U-separation on a flat-plate
- Stall cells on a NACA0015 airfoil
- Receptivity and Sensitivity of LSB on a flat plate

Compressible Flow

- The Howarth/Briley bubble in subsonic flow
- Shock/Boundary-Layer Interaction (SBLI) on a semi-infinite plate at Mach 2
- SBLI on a 45° wedge

Focus on the (stationary, self-excited) global mode alone

Numerical considerations

MASSIVELY PARALLEL SOLUTION OF THE EVP

- Ten years later…
  - Incoming TS waves at the inflow boundary
    (besides the homogeneous Dirichlet BCs used in THD)
  - 400x100 points per spatial direction used to resolve the amplitude function of the eigenmodes
    (as opposed to 60x40 in THD)
  - 25k CPU hrs (= 25 hrs x 1000 procs) per wavenumber
    (as opposed to 24 CPU hrs serial computing time on a single processor in THD)

…permit solving substantially larger (but not all) problems,

- on Mare Nostrum at BSC and (the Petaflop) Blue-Gene/P at FZJ
  (but Jürgen Seidel finally got access to DoD HPC machines)

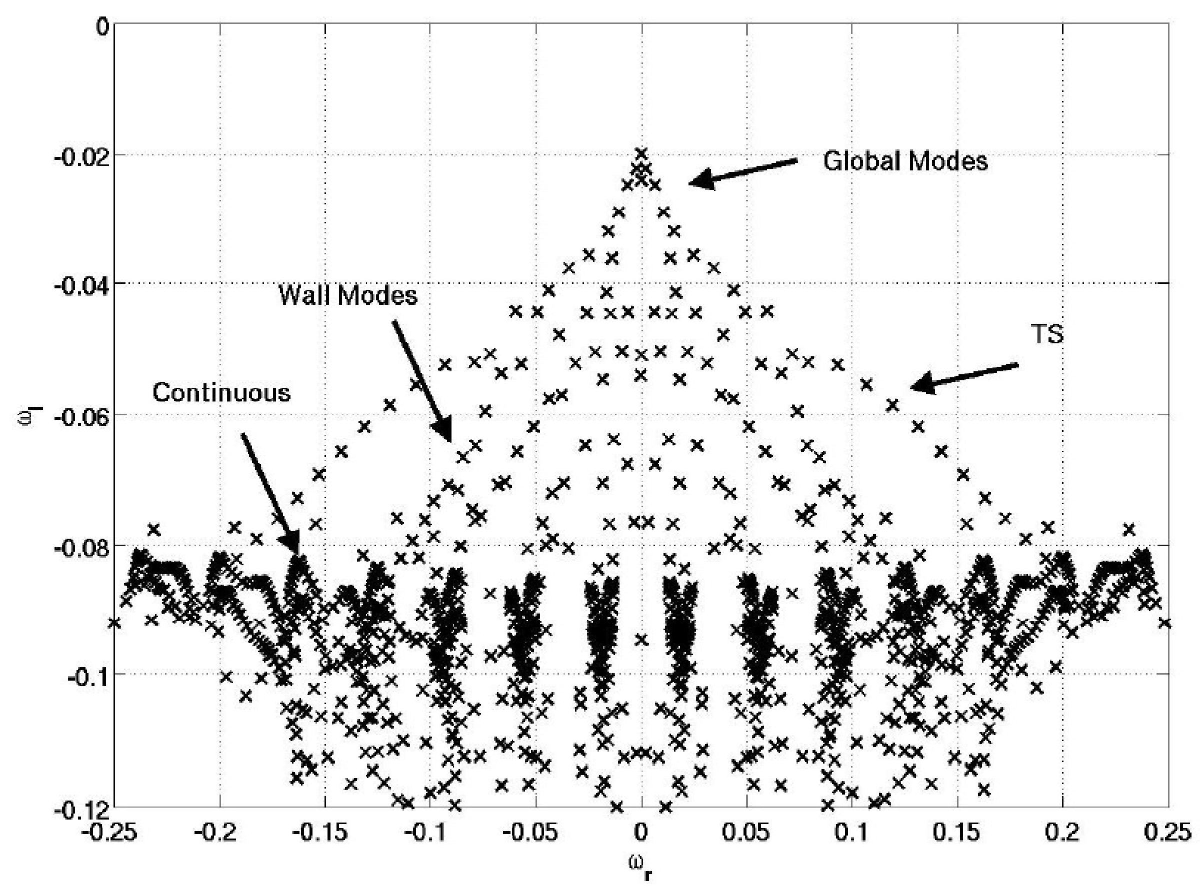
Rodríguez & Th AIAA J (2009 – accepted)

Classification of global modes of LSB flow

GLOBAL MODES IN LSB FLOW ON A FLAT PLATE

Case: Re_{δ^*}=500 at inflow, Re_{δ^*}=700 at outflow, **Separation Bubble**

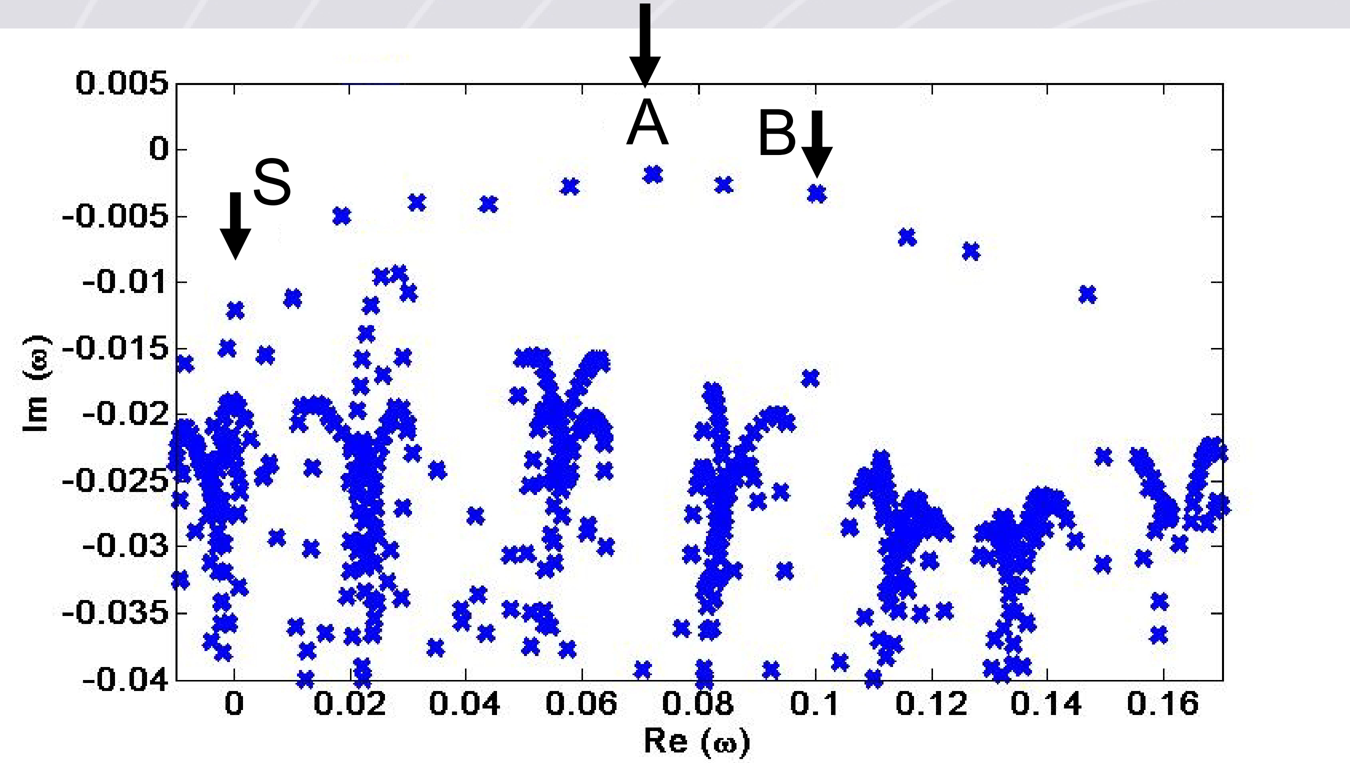
Boundary conditions: Dirichlet at inflow & Extrapolation at outflow



$\beta = 1$

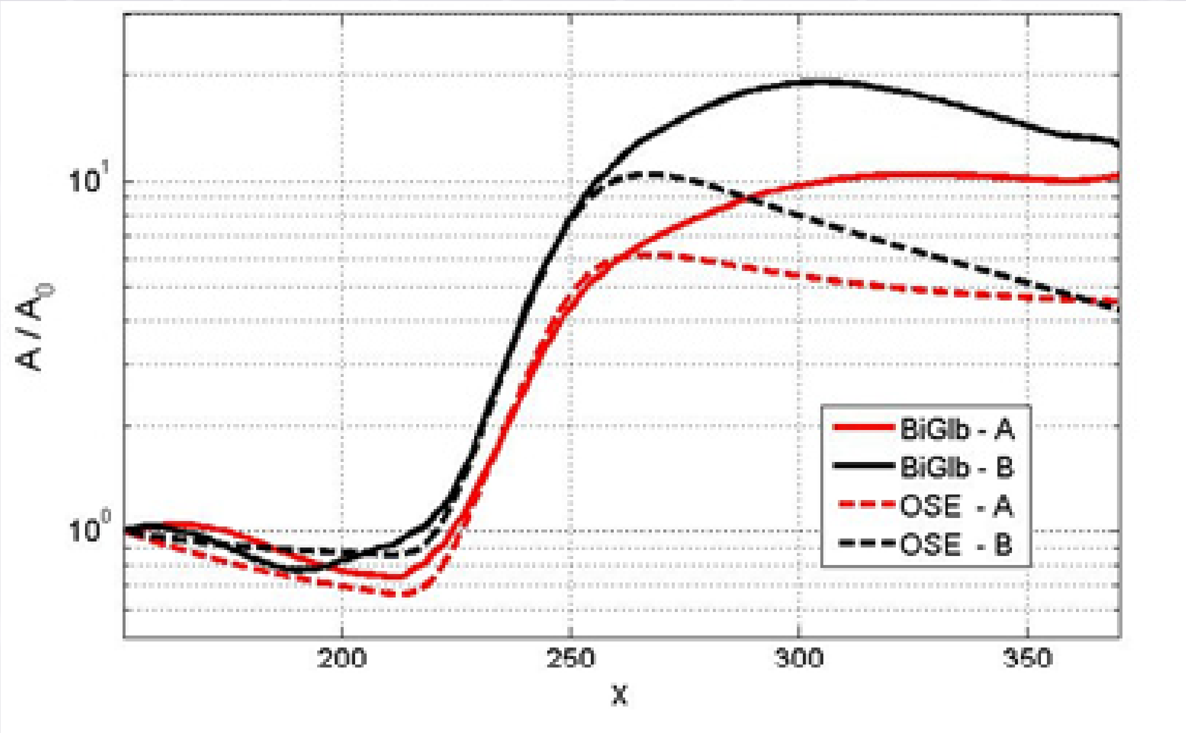
TYPICAL FLAT-PLATE GLOBAL EIGENSPECTRUM

- Composed of discrete and continuous branches
- Focus discussion on two traveling (~~and the leading stationary)~~ global eigenmodes



Comparison of traveling modes with OSE

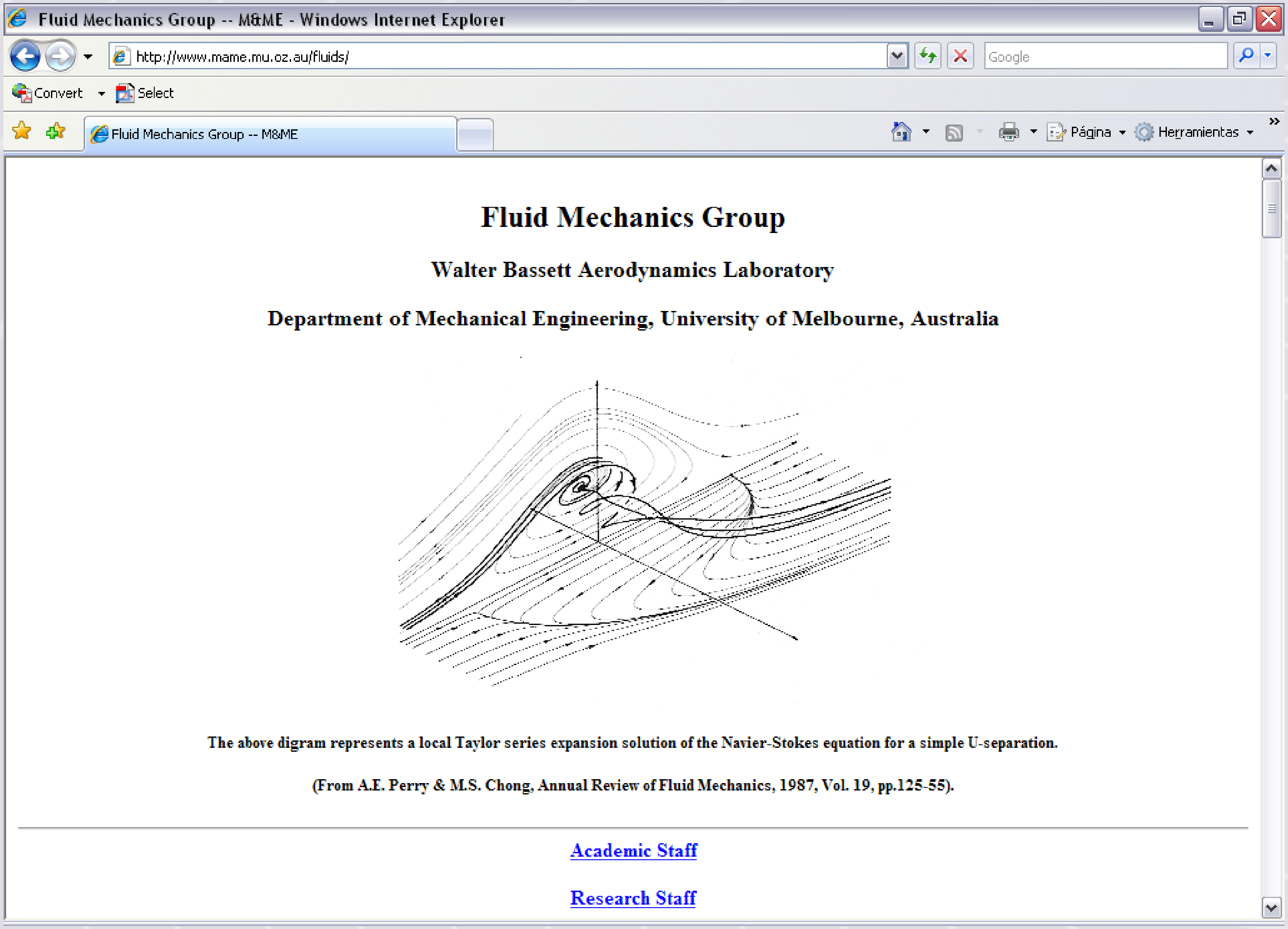
- Extract "spatial amplification" from successive peaks of the (2d) global eigenfunction;
- Run a spatial OSE at successive downstream locations;
- Compare



Extracting physics out of eigenspectra:

- **U-separation** on a flat plate

U-SEPARATION



Fluid Mechanics Group

Walter Bassett Aerodynamics Laboratory

Department of Mechanical Engineering, University of Melbourne, Australia

The above digram represents a local Taylor series expansion solution of the Navier-Stokes equation for a simple U-separation.

(From A.E. Perry & M.S. Chong, Annual Review of Fluid Mechanics, 1987, Vol. 19, pp.125-55).

Academic Staff

Research Staff

“U-SHAPED SEPARATION” – 1984

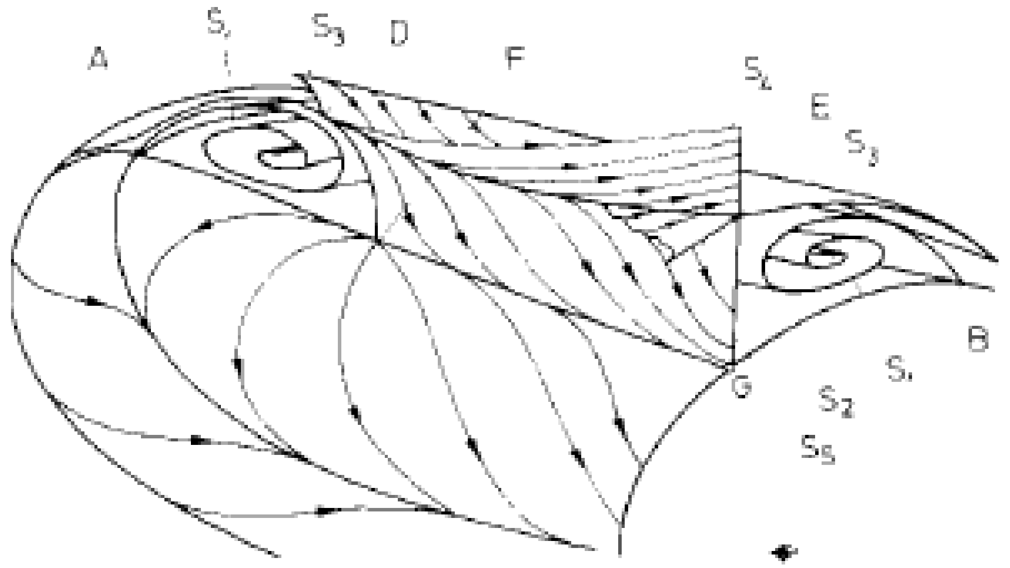
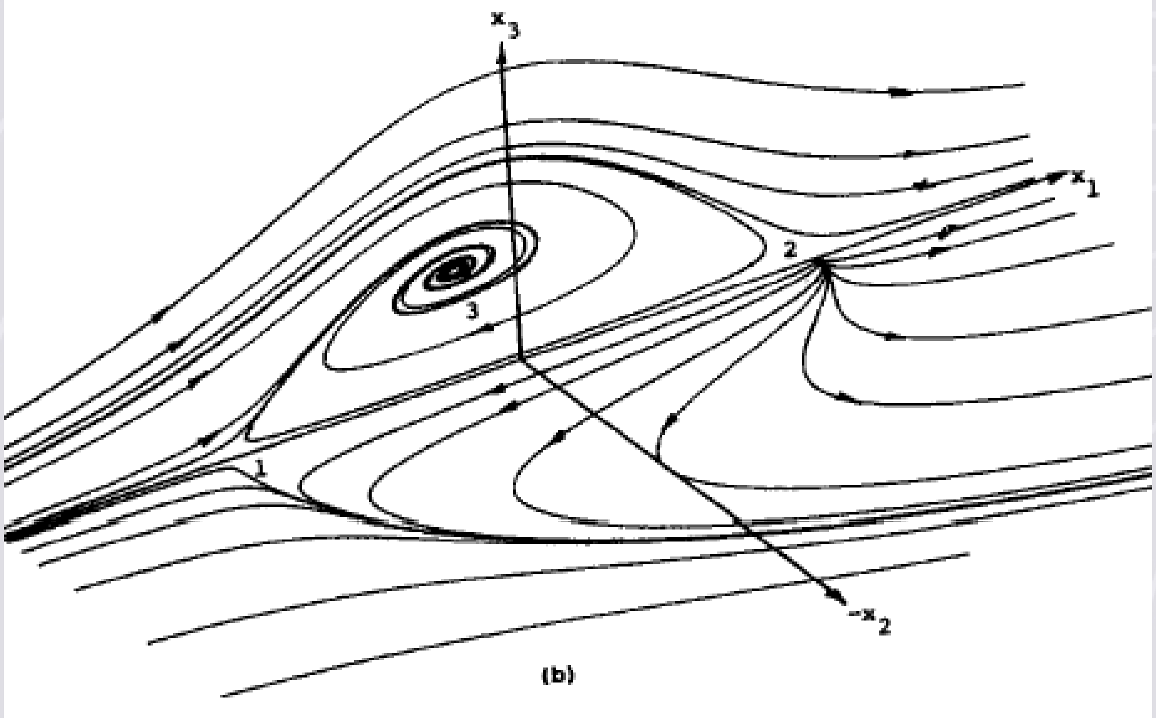
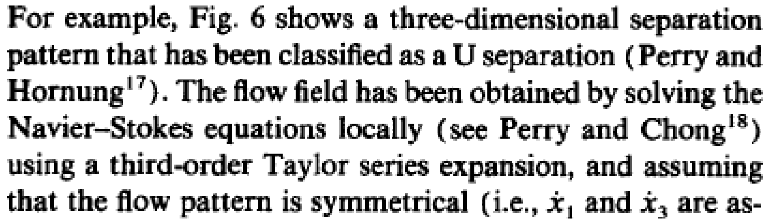


FIG. 17: Perspective view of the free streamsurface sheets and wall streamlines of simple U-shaped separation

Hornung, Perry Z. Flugwiss. Weltraumforsch.(1984) 8(2):77-87

U-SEPARATION



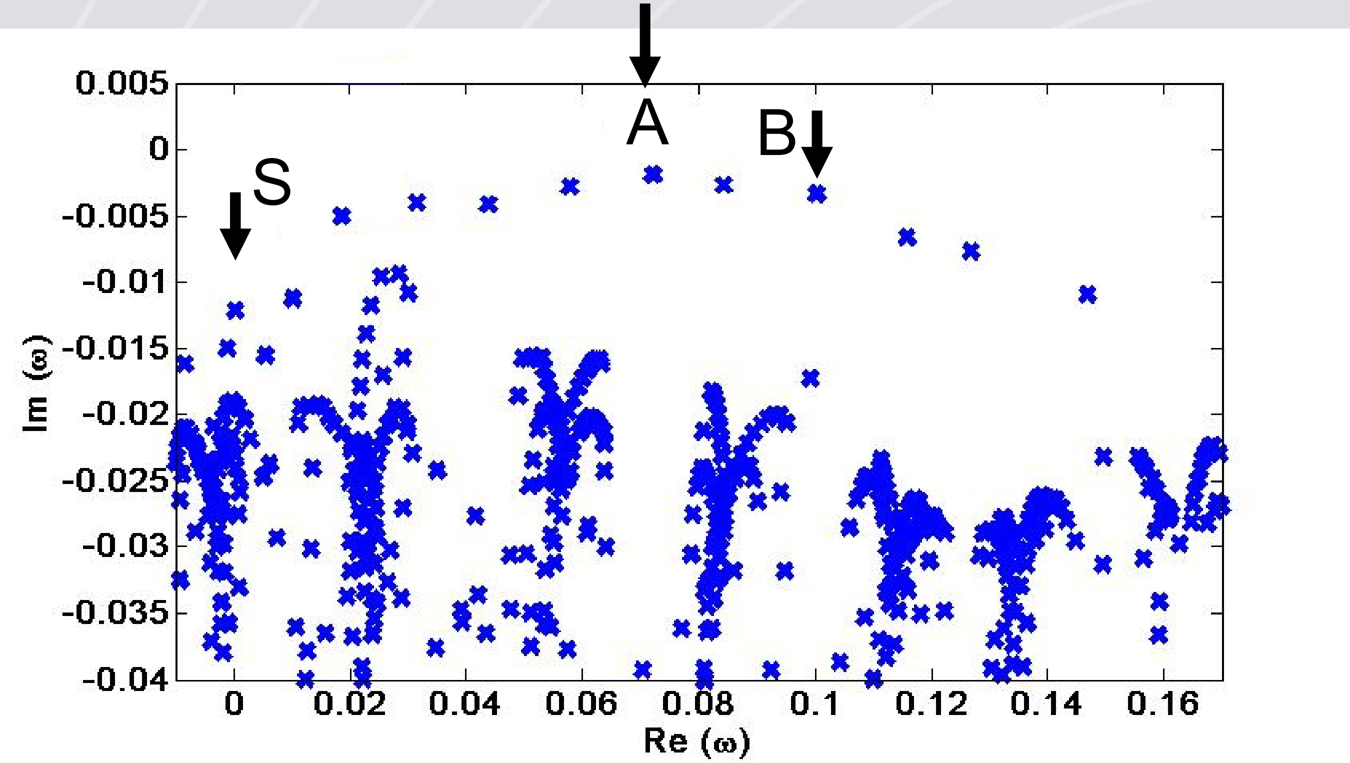


For example, Fig. 6 shows a three-dimensional separation pattern that has been classified as a U separation (Perry and Hornung[17]). The flow field has been obtained by solving the Navier–Stokes equations locally (see Perry and Chong[18]) using a third-order Taylor series expansion, and assuming that the flow pattern is symmetrical (i.e., $\dot{x}_1$ and $\dot{x}_3$ are as-

Chong, Perry, Cantwell Phys. Fluids A (1990) 2(5):765-777

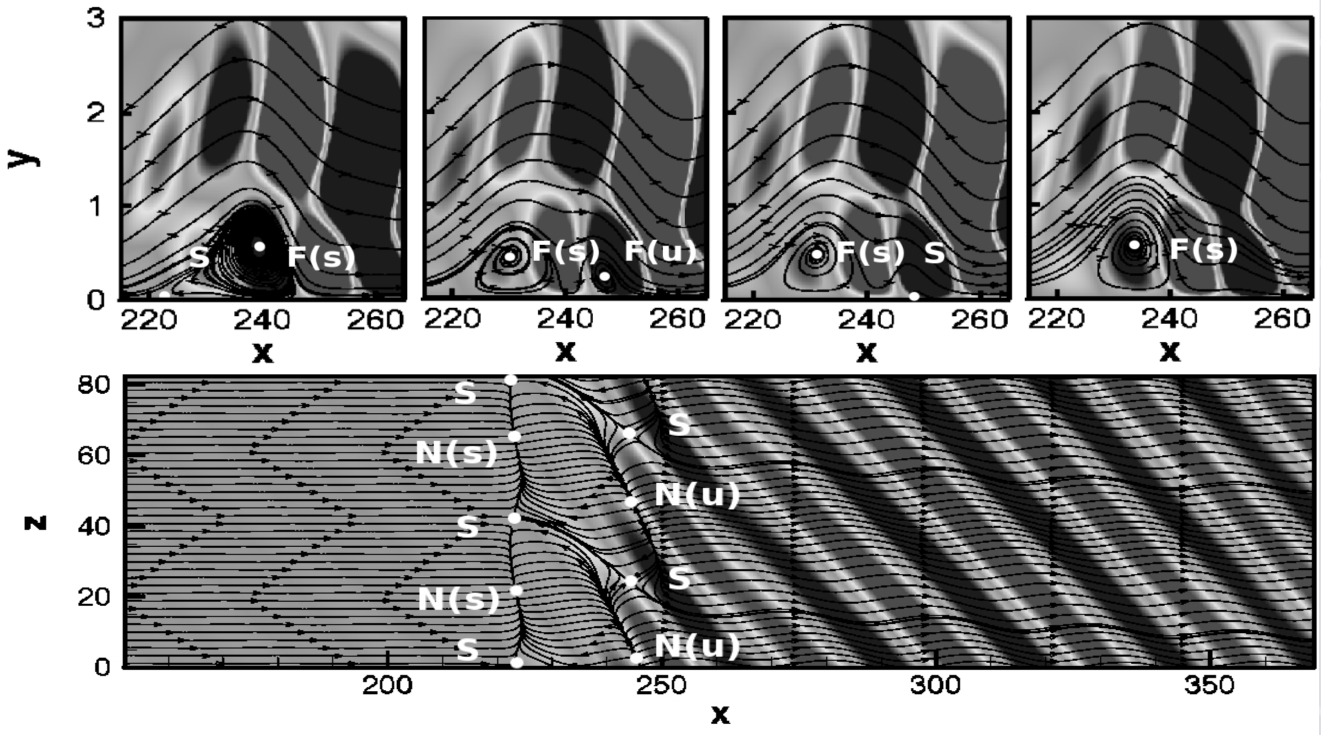
TYPICAL FLAT-PLATE GLOBAL EIGENSPECTRUM

- Composed of discrete and continuous branches
- Focus on (~~two traveling and~~) the leading stationary global eigenmode



Critical Points of (BF + ε A)

- **Reconstruct a composite flowfield, using the steady basic state and the leading global eigenmode**
- **Identify critical points and their nature**



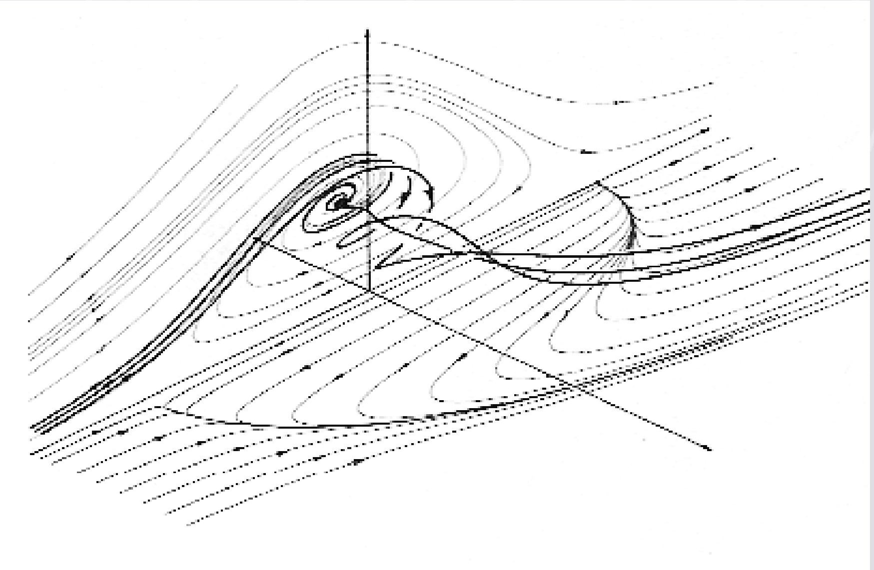
S: Saddle N: Node F: Focus C: Center

(s): stable (u): unstable

Critical Points of (BF + ε S)

- **Critical point analysis of composite flow**

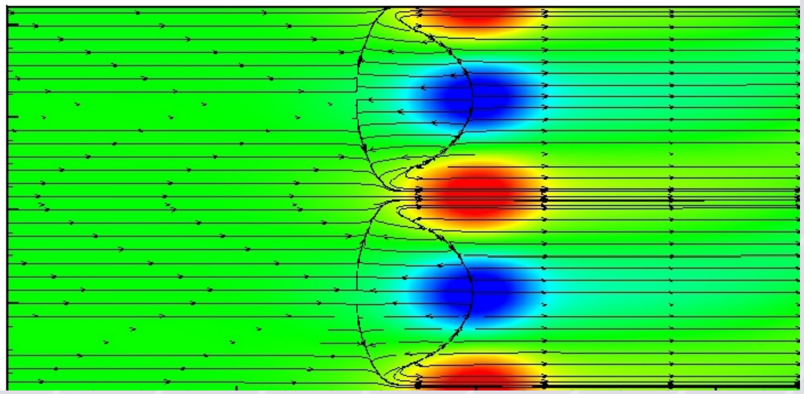
Eigenvalue spectrum



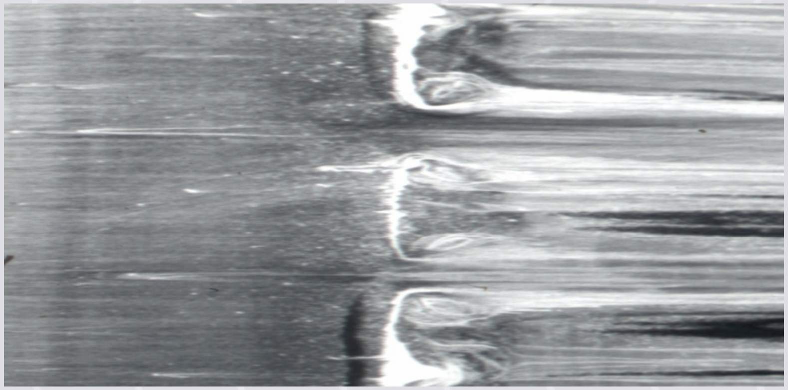
BF + ε (Global Mode)

Rodríguez & Th J Fluid Mech (2009 – submitted)

U – SEPARATION



Present computations

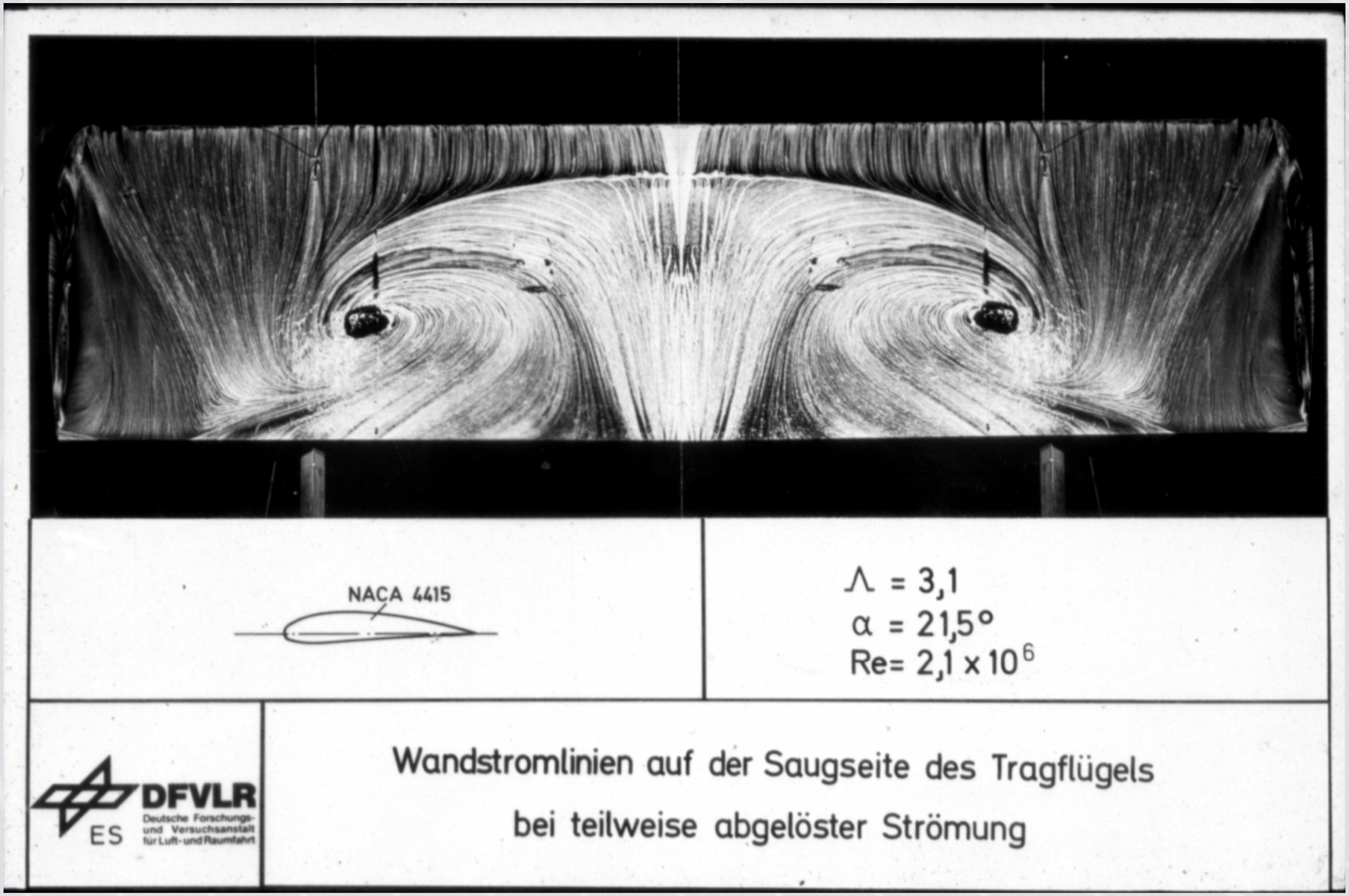


Bippes (198?)

Extracting physics out of eigenspectra:

- **Stall Cells** on an Airfoil

STALL CELLS ON AIRFOILS



NACA 4415

$\Lambda = 3{,}1$
$\alpha = 21{,}5°$
$Re = 2{,}1 \times 10^6$

DFVLR
Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt
ES

Wandstromlinien auf der Saugseite des Tragflügels
bei teilweise abgelöster Strömung

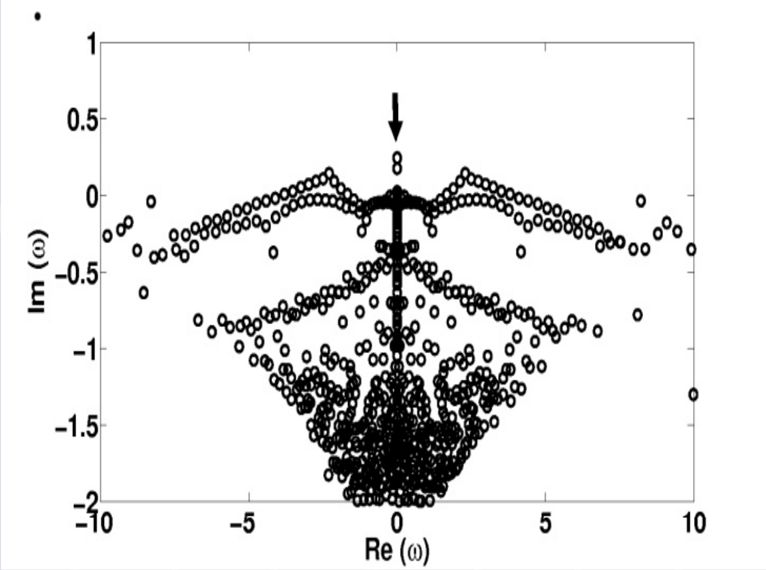
Bippes (198?) – courtesy of H. Hornung via H. Fasel

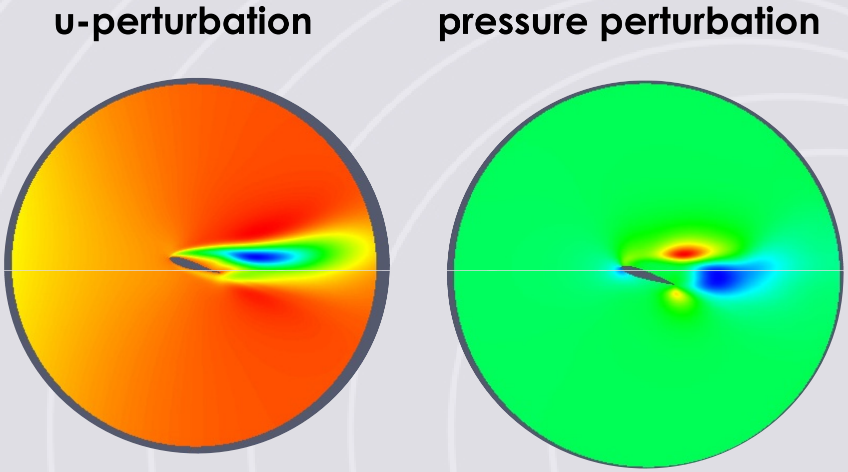
TYPICAL RESULTS ON A STALLED AIRFOIL

- **Critical point analysis of composite flow**

Eigenvalue spectrum

Leading stationary eigenmode

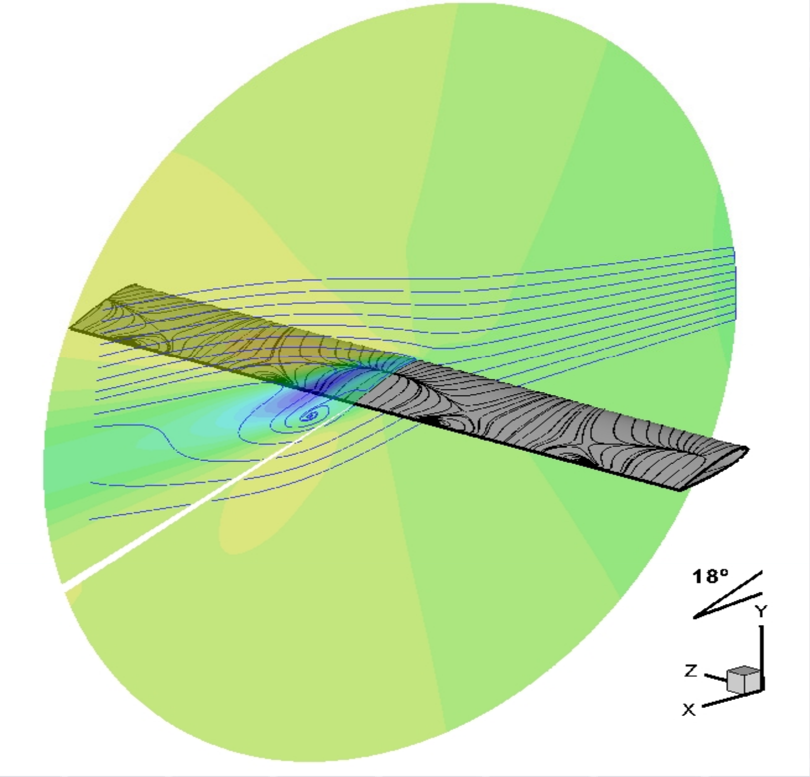




Kitsios, Rodríguez, Th, Ooi, Soria J Comput Phys 228:7181-7196 (2009)

Critical Points of (BF + ε GlobalMode)

- **Stall-cells** appear on the airfoil, as result of **linear modal amplification of the leading stationary global mode**

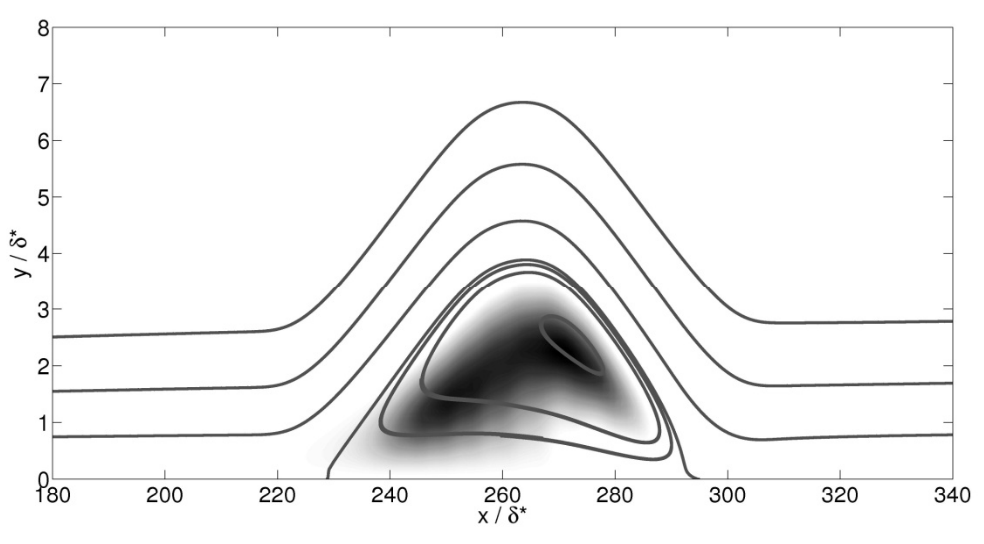


Rodríguez & Th Theor Comp Fluid Dyn (2009 – in review)

Flow Control of LSB

SENSITIVITY OF LSB

- The kernel of the direct/adjoint coupling (Luchini 2003) permits identifying the region of maximal feedback region…



- … it coincides with the primary recirculation center
- (a result not unexpected, really)

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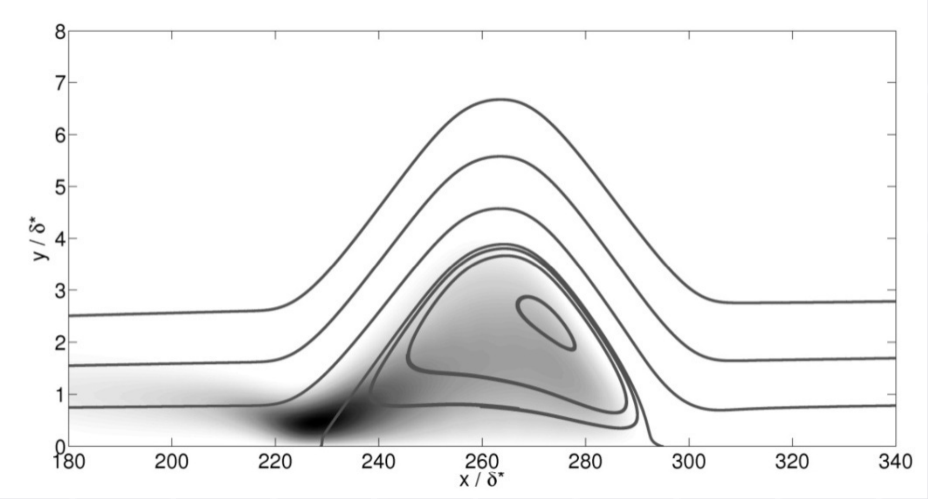
RECEPTIVITY OF LSB ON A FLAT-PLATE

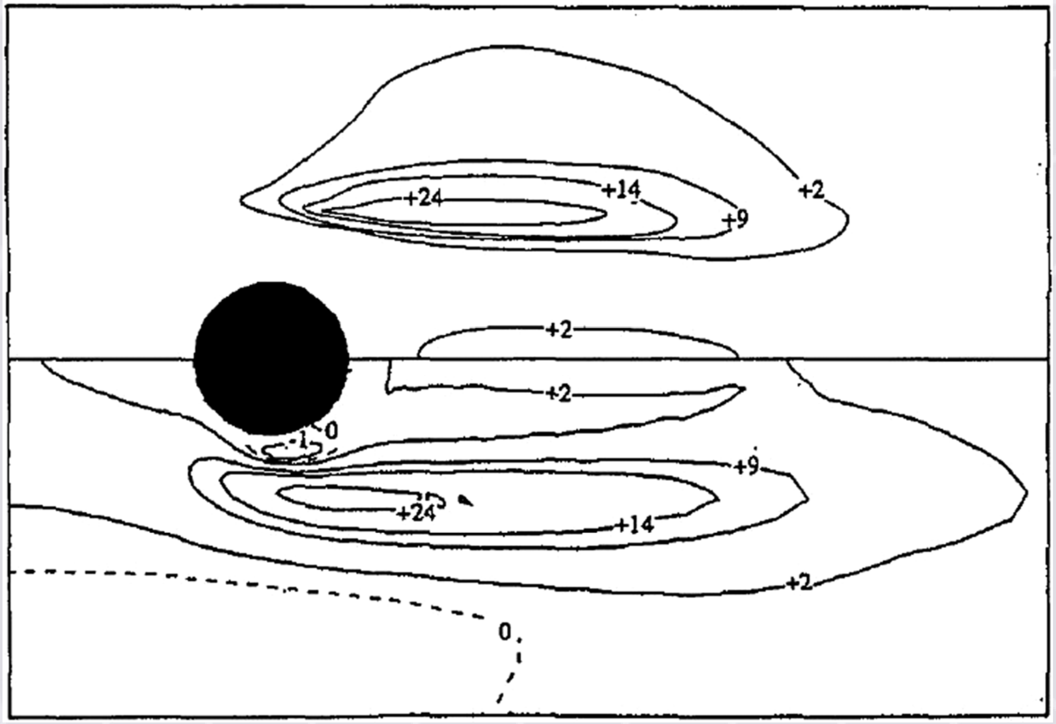
- **Solution of the adjoint eigenvalue problem permits identifying the maximally receptive region (dominant streamwise velocity perturbation)**



- **… it coincides with the primary separation line**
- **NB. Analysis is meaningful due to homogeneous Dirichlet BCs imposed upstream (direct) / downstream (adjoint) EVP**

WHAT CAN THIS KNOWLEDGE DO FOR US?

- Predict the actuator placement without prior knowledge (or ad-hoc assumptions)

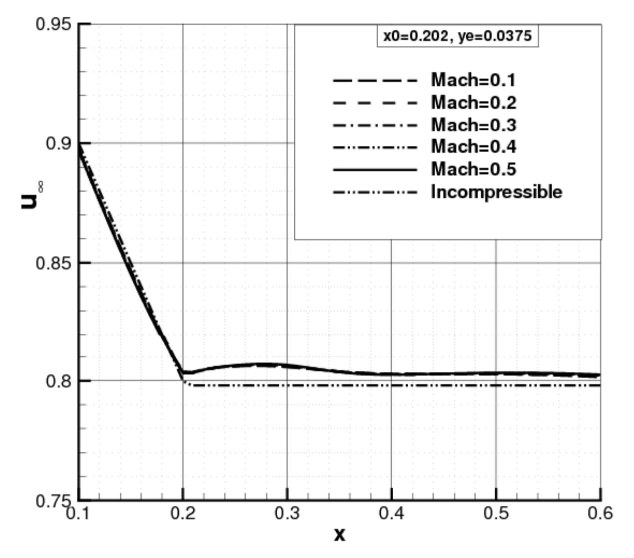


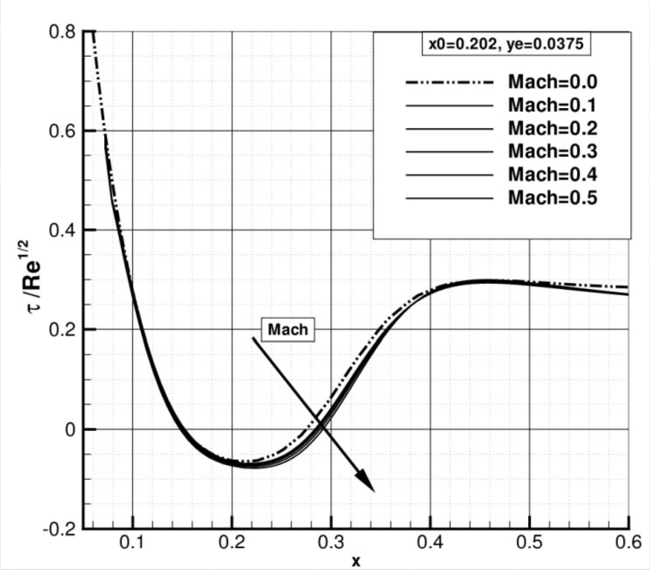
Hill AIAA 1992-0067; Giannetti, Luchini JFM (2007)

Compressibility effects – subsonic flow

MACH # EFFECT ON HOWARTH/BRILEY LSB

- Linear pressure increase (compressible) v linear deceleration (incompressible) in the free-stream





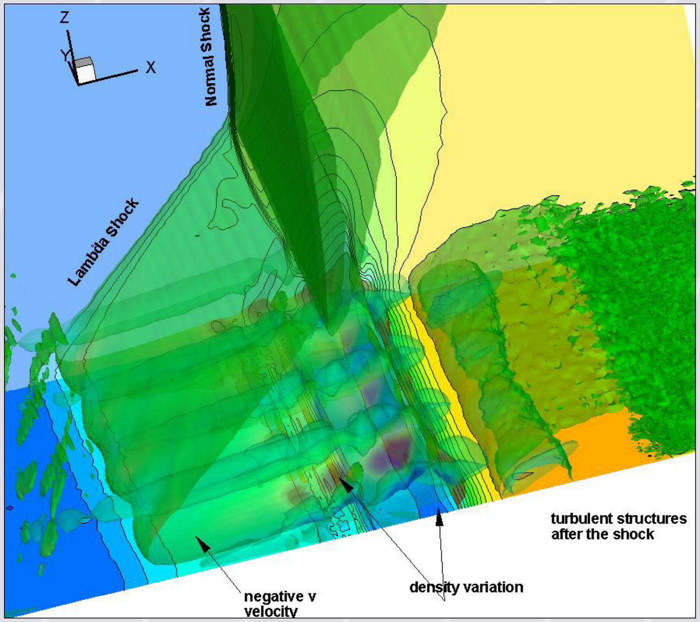
- No major differences in integral quantities have been found, ie.
- Quantitative but no qualitative differences of instability results
- Work in progress, in collaboration with Stanford U.

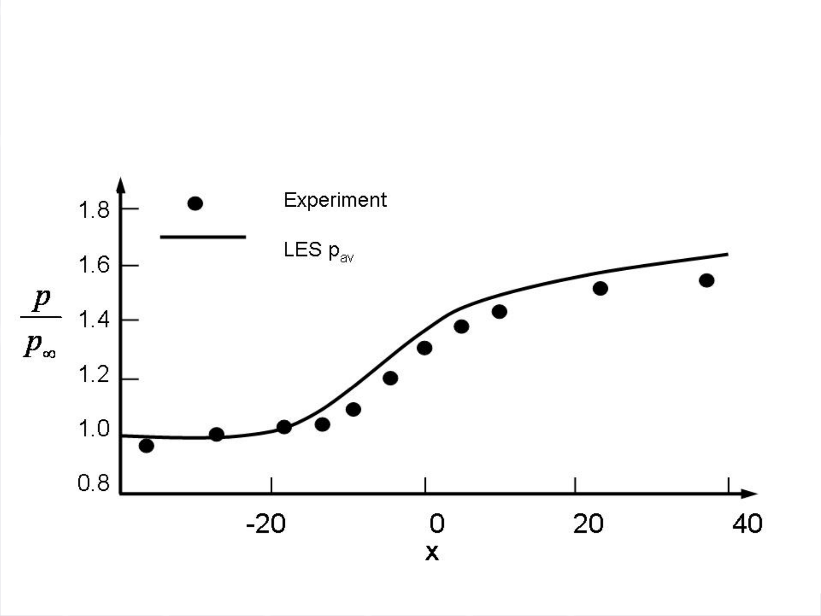
Valero & Th AIAA Pap 2008-0593

Compressibility effects – supersonic flow

SHOCK / BOUNDARY-LAYER INTERACTION

- **Typical LES result at Re_δ = 10k**



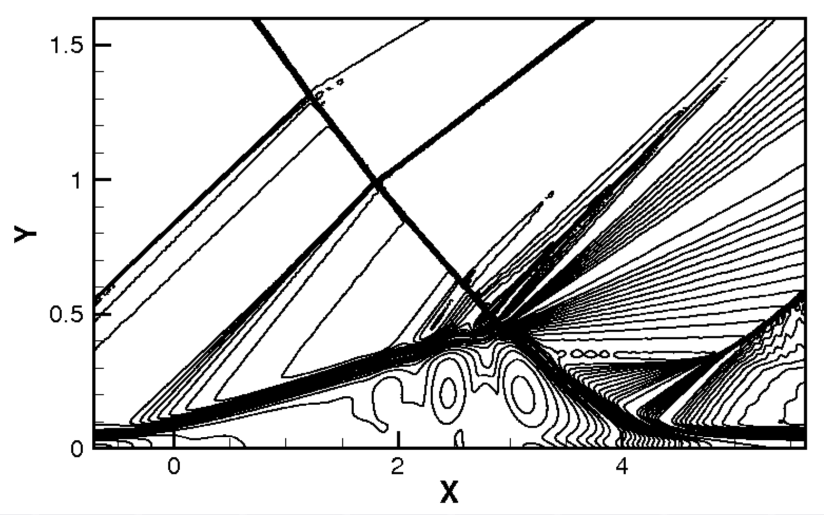


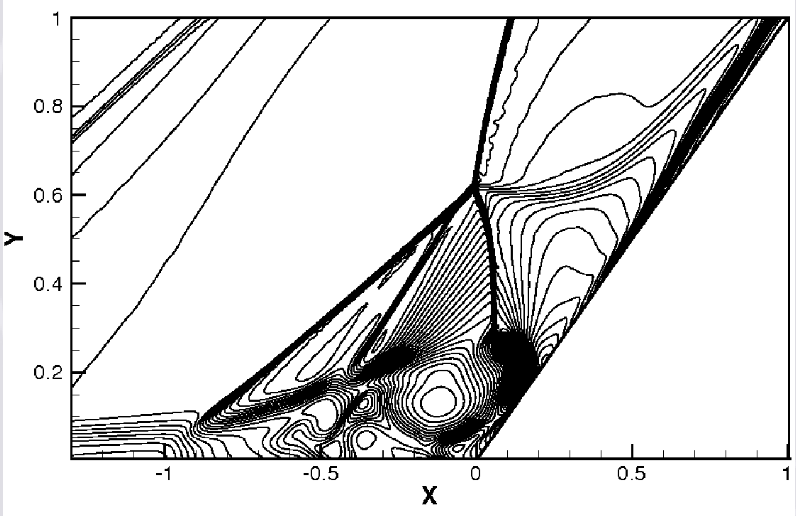
- **Origin of unsteadiness?**
- **Origin of spanwise periodic structures ?**

Ekaterinaris AIAA J (2004) 42(3):493-500

SBLI & 45º COMPRESSION CORNER – BFs

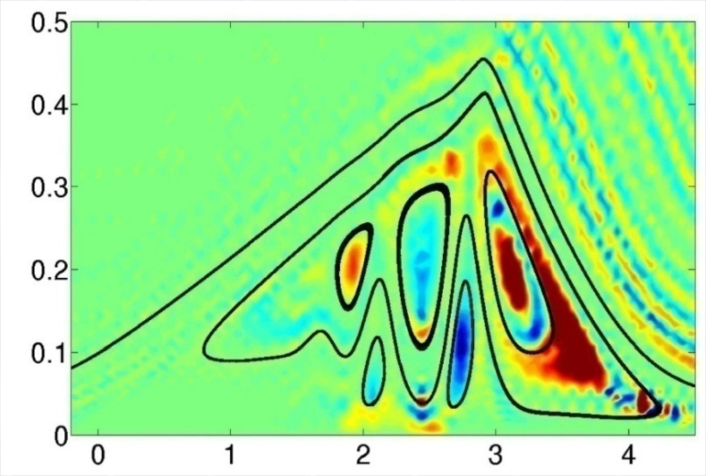
- **Basic states obtained by high-order accurate, low-diffusion WENO schemes (Ekaterinaris)**
- **Flat plate leading edge included at upstream end of both domains**
- **Finite-angle wedge in compression corner (no triple-deck)**
- **Both flows at $5000 < Re_L < 20000$, $Ma = 2$ and 2.5**
- **Unsteadiness identified by DNS at $Re_L \approx 25k$**

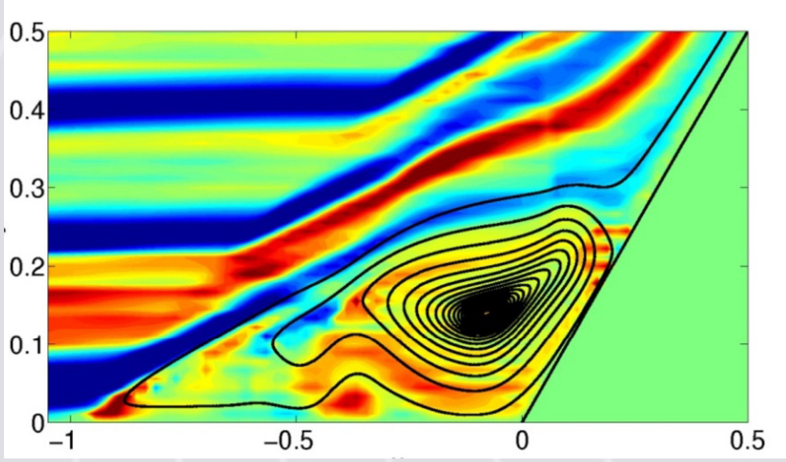




GLOBAL “MODES”

- Compressible BiGlobal EVP solved at $5000 < Re_L < 20000$ by
  - Spectral collocation (SBLI on flat plate)
  - Immersed boundary (45° compression corner)
- Entire BF domain considered – shocks not treated (≠ Crouch)
- Qualitatively reasonable results,…





- …but spectra are not converged (despite very large resolutions)
- Work in progress, in collaboration with with Patras U.

SUMMARY (I / II)

- In the last 3 years, global linear instability of LSB has been revisited, using state-of-the-art hardware and algorithms
- Eigenspectra of LSB flows have been understood and classified in branches of known and newly-discovered eigenmodes
- Major achievements:
  - World-largest numerical solutions of global eigenvalue problems are routinely performed
  - Key aerodynamic phenomena have been explained via critical point theory, applied to our global mode results
- Theoretical foundation for control of LSB flows has been laid

SUMMARY (II / II)

- Global mode of LSB at the origin of observable phenomena
  - U-separation on semi-infinite plate
  - Stall cells on (stalled) airfoil
- Receptivity/Sensitivity/AFC feasible (practical?) via
  - Adjoint EVP solution
  - Direct/adjoint coupling (the Crete connection)
- Minor effect of compressibility on global instability in the subsonic compressible regime
- Global instability analysis of LSB in realistic supersonic flows apparently quite some way down the horizon

(Saric joke # 431: “an imaginary, ever-receding line”)

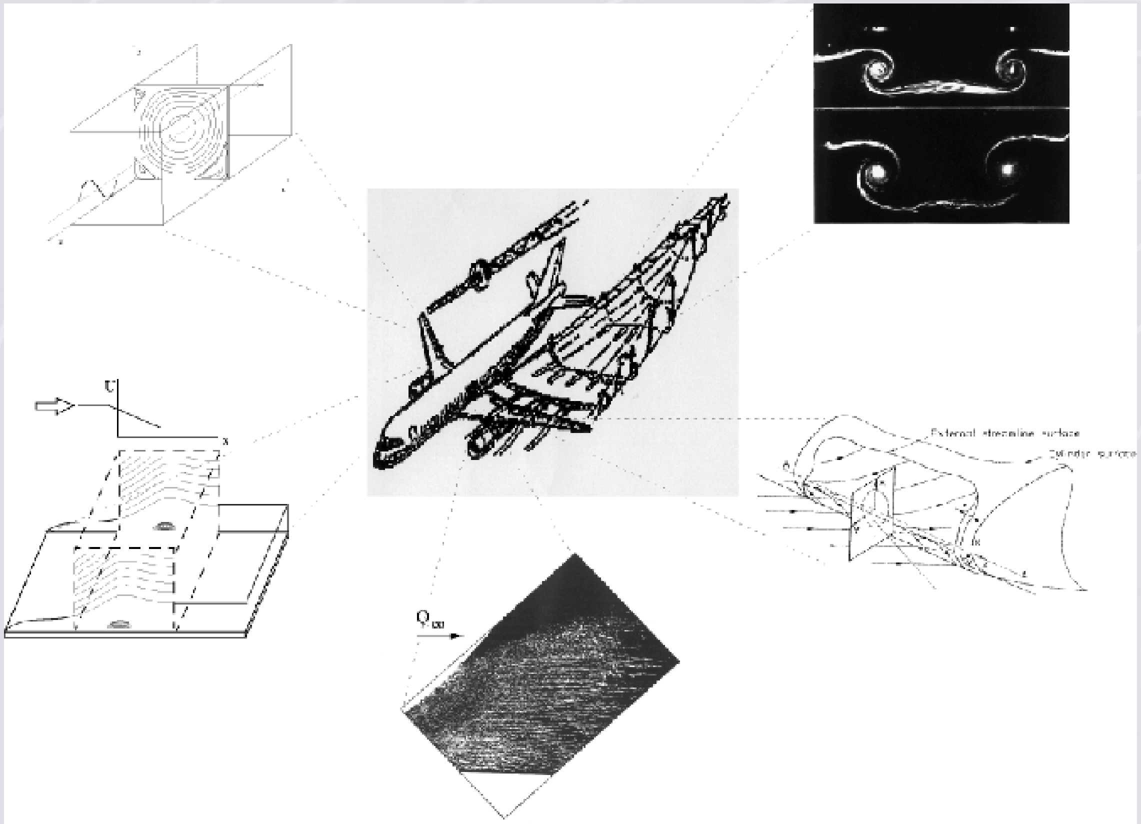
FUTURE CHALLENGES AND WORK DIRECTIONS

- From a physical (and theoretical) point of view
  - Continue with the analysis of EVP results
  - Instability analysis of turbulent flows (obtain EVP spectra of 2.5D flows)
  - Embed instability analysis into (AFC) flow control concepts (for 2.5D flows)
  - Extend global instability tools in 3D flows

- From a numerical point of view
  - Devise new algorithms for the efficient parallel solution of (massive) eigenvalue problems

Thank You

GLOBAL FLOW INSTABILITY AND CONTROL IV



Crete, Greece, Sept 28 – Oct 2, 2009

ADDITIONAL MATERIAL

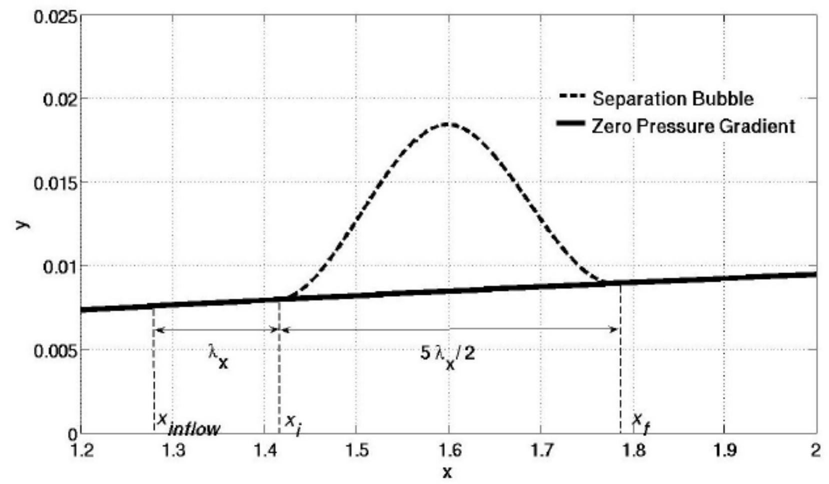
BASIC LSB FLOW ON A FLAT PLATE

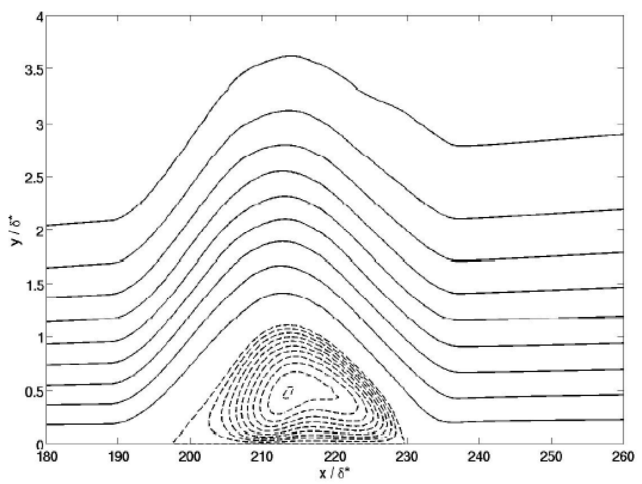
Boundary Layer transformation:

$$\xi = \frac{x}{L} \qquad \eta = y\sqrt{\frac{U_e}{\nu x}} \quad \longrightarrow \quad \Psi = \sqrt{U_e \nu x}\, f(\xi,\eta)$$

Separated states recovery:

- Reyhner and Flügge-Lotz approximation
- Displacement thickness imposed





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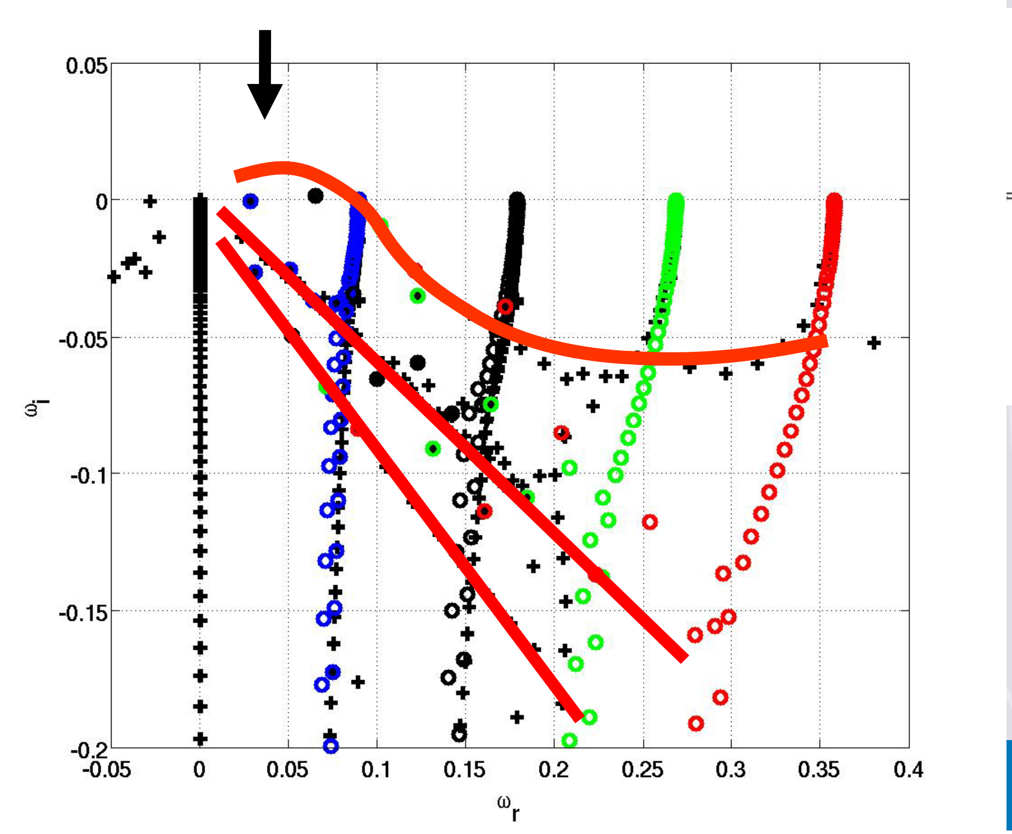
COMPARISON WITH TEMPORAL OSE

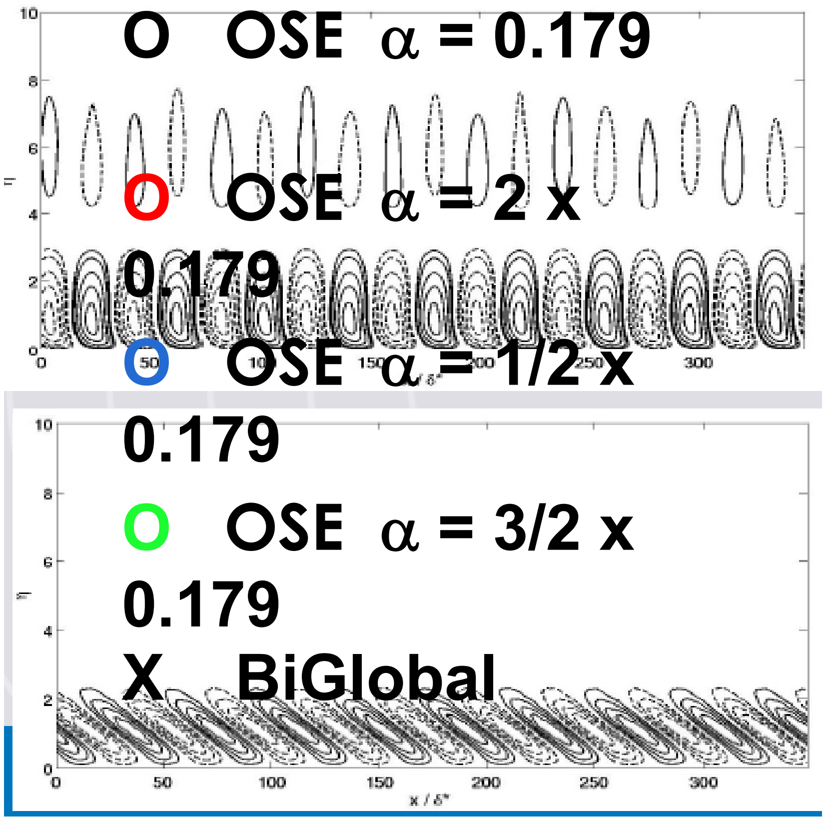
Basic Flow: Artificial parallel Blasius

Mack's Case: Re = 580, α = 0.179 (Mack JFM 1976)

Streamwise extension: L = 10 x 2 π / α

Periodic boundary conditions





O OSE α = 0.179

O OSE α = 2 x 0.179

O OSE α = 1/2 x 0.179

O OSE α = 3/2 x 0.179

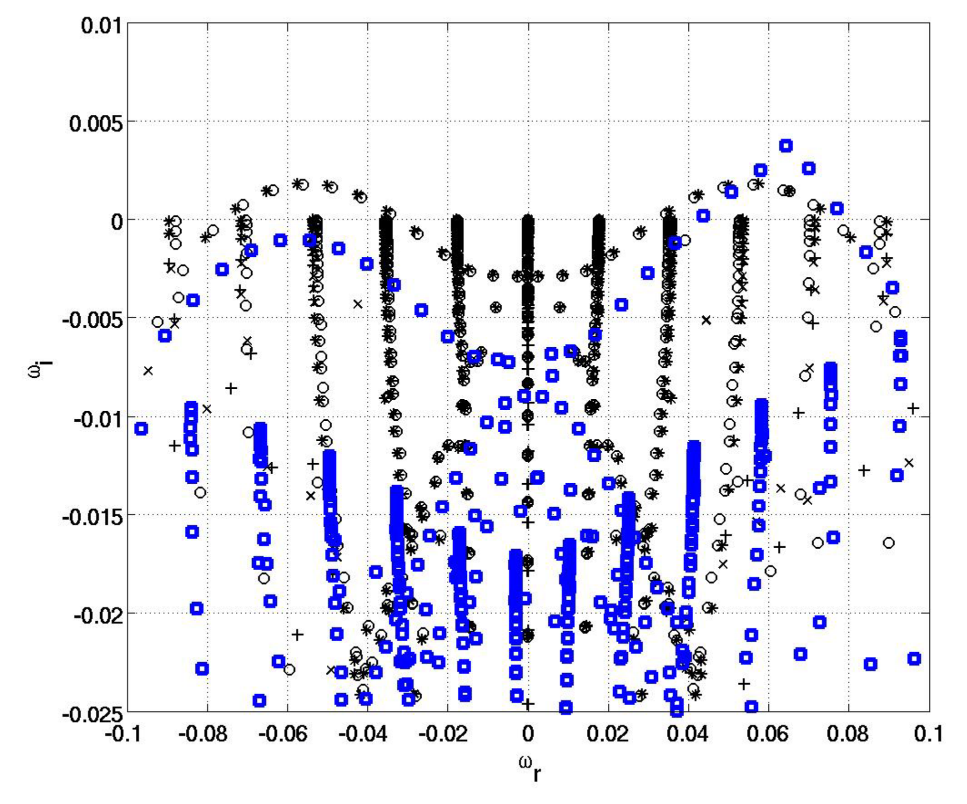
X BiGlobal

FURTHER COMPARISONS WITH TEMPORAL OSE

Basic Flow: Artificial parallel Blasius

Mack's Case: Re = 580, α = 0.179 (Mack JFM 1976)

Streamwise extension: L = 10 x 2 π / α



Boundary conditions:

X Periodicity - Fourier

+ Periodicity - Chebyshev

O Robin inflow & outflow

☐ **Robin inflow & Extrapolation outflow**

COMPARISONS WITH SPATIAL OSE

Case: $Re_{\delta*}$=500 at inflow, $Re_{\delta*}$=700 at outflow

Analysis 1:

- **Basic Flow:** Artificial parallel Blasius
- **Boundary conditions:** Robin* at inflow & outflow

Analysis 2:

- **Basic Flow:** Artificial parallel Blasius
- **Boundary conditions:** Robin* at inflow & extrapolation at outflow

Analysis 3:

- **Basic Flow:** Real Blasius boundary layer
- **Boundary conditions:** Robin* at inflow & extrapolation at outflow

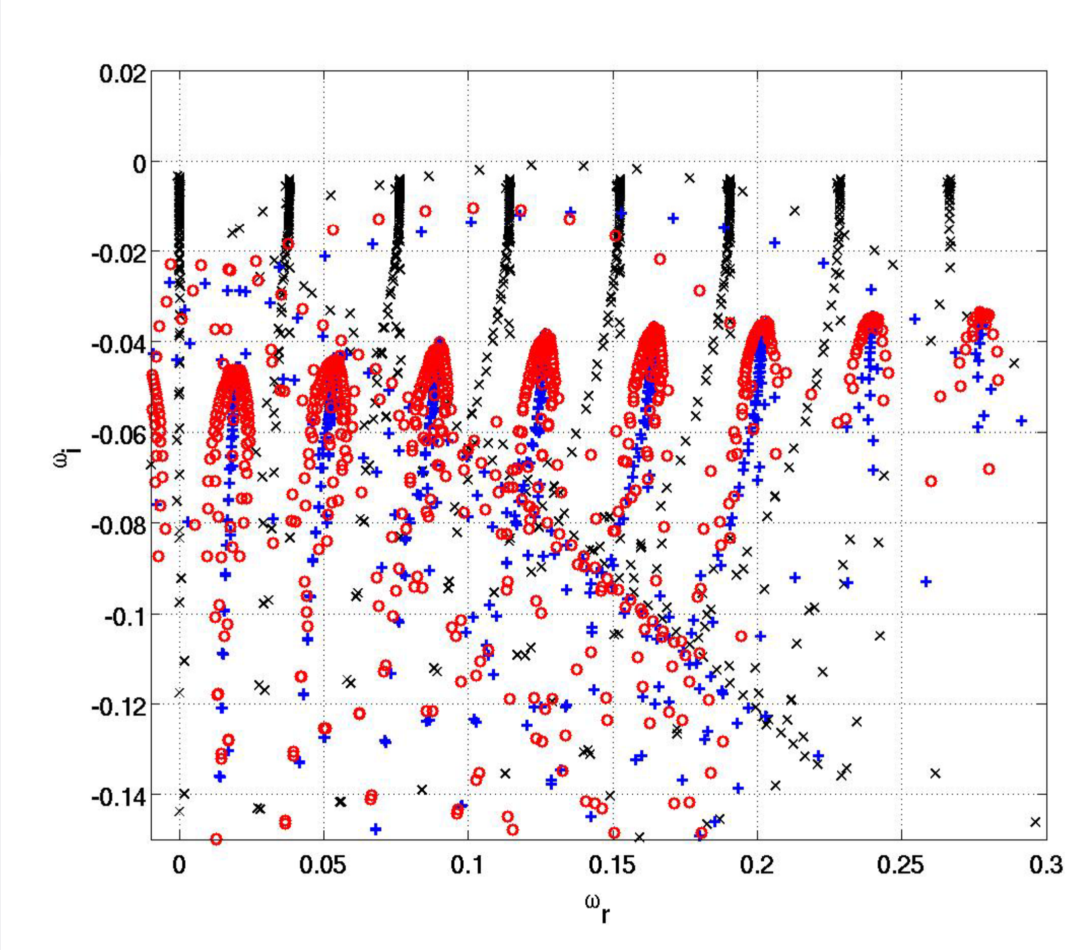
*** Robin boundary condition of Ehrenstein & Gallaire JFM 2005:**

$$\frac{\partial \hat{\mathbf{q}}}{\partial x} = \mathrm{i}\left(\alpha_{r,0} + \frac{\partial \alpha_r}{\partial \omega_r}(\omega_0)\cdot(\omega - \omega_0)\right)\hat{\mathbf{q}}$$

FURTHER COMPARISONS WITH SPATIAL OSE

Case: $Re_{\delta*}$=500 at inflow, $Re_{\delta*}$=700 at outflow

Robin boundary condition evaluated at: $\omega_0 = 0.13$



Analysis:

1 **X** Parallel Blasius, Robin + Robin

2 **+** Parallel Blasius, Robin + Extrapolation

3 **O** Real Blasius, Robin + Extrapolation

PUBLICATIONS

Journals

- **[J-4] Rodríguez, D., Theofilis, V. 2009 Massively Parallel Numerical Solution of the Bi-Global Linear Instability Eigenvalue Problem Using Dense Linear Algebra *AIAA Journal*, accepted for publication, DOI: 10.2514/1.42714**
- **[J-3] Kitsios, V., Rodríguez, D., Theofilis, V., Ooi, A., Soria, J. 2009 BiGlobal stability analysis in curvilinear coordinates of massively separated lifting bodies. *Journal of Computational Physics*, accepted for publication, DOI: 10.1016/j.jcp.2009.06.011**
- **[J-2] Rodríguez, D., Theofilis, V. 2009 On the birth of stall-cells on airfoils. *Theoretical and Computational Fluid Dynamics* (accepted for publication).**
- **[J-1] Rodríguez, D., Theofilis, V. 2009 Structural changes induced by global linear instability of laminar separation bubbles. *Journal of Fluid Mechanics* (submitted for publication).**

Book Chapters

- **[B-2] Theofilis, V. 2009 Role of instability theory in flow control. In *Fundamentals and Applications of Modern Flow Control* (Joslin RD, Miller D, eds.) ISBN 978-1-56347-938-0, AIAA Progress in Astronautics and Aeronautics, vol. 231, pp. 73-114.**
- **[B-1] de Vicente, J., Rodríguez, D., González, L. Theofilis, V. 2008. High-order numerical methods for BiGlobal flow instability analysis and control. In *Associação Brasileira de Ciências Mecânicas, Volume 6 tomo 2: Turbulência.* 6ª Escola de Primavera em Transição e Turbulência, Univ. São Paulo, Sao Carlos, 22- 26 Sept. 2008, (M. Teixeira Mendonça, M. Faraco de Medeiros, eds.), pp. 1-123.**

Conferences

- **[C-8] Rodriguez, D., Ekaterinaris, J., Valero, E., Theofilis, V. 2009 On receptivity and modal linear instability of laminar separation bubbles at all speeds. Seventh IUTAM Symposium on Laminar-Turbulent Transition, Stockholm, Sweden, June 23-26, 2009. Springer (to appear).**
- **[C-7] Theofilis, V. Rodríguez, D. 2009 Global Linear Instability on Laminar Separation Bubbles – revisited: U-separation and the Birth of Stall Cells on Airfoils. CEAS/KATnet II Conference on Key Aerodynamic Technologies, Bremen, Germany, May 12-14, 2009. 12pp. ISBN 978-3-00-027782-5.**
- **[C-6] Kitsios, V., Rodriguez, D., Theofilis, V., Ooi, A., Soria, J. 2008. BiGlobal instability analysis of turbulent flow over an airfoil at an angle of attack layer. AIAA 38th Fluid Dynamics Conference And Exhibit, Seattle, June 23-26, 2008. AIAA Paper 2008-4384.**
- **[C-5] Rodriguez, D., Theofilis, V. 2008 On instability and structural sensitivity of incompressible laminar separation bubbles in a flat-plate boundary layer. AIAA 38th Fluid Dynamics Conference And Exhibit, Seattle, June 23-26, 2008 AIAA Paper 2008-4148**
- **[C-4] Valero, E., Theofilis, V. 2008 Compressibility Effects in Howarth's Separation Bubble on a Flat Plate. AIAA 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 7-10, 2008, AIAA Paper 2008-0593.**
- **[C-3] Rodriguez, D., Theofilis, V. 2008 Massively Parallel Numerical Solution of the BiGlobal Linear Instability Eigenvalue Problem. AIAA 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 7-10, 2008. AIAA Paper 2008-0594.**
- **[C-2] Theofilis, V. 2007 On instability properties of incompressible laminar separation bubbles on a flat plate prior to shedding. AIAA 45th Aerospace Sciences Meeting, Reno, NV, Jan 8-11, 2007. AIAA Paper 2007-0540.**
- **[C-1] Theofilis, V. 2007 Global instability and control of laminar separation bubbles: Theoretical background, basic ow documentation, algorithmic developments and validation. IUTAM Symposium on Unsteady Separated Flows and their Control. Corfu, Greece, June 18-22, 2007. Springer (to appear). ISBN: 978-1-4020-9897-0.**

TECHNICAL EXCHANGES

- U of Arizona
  - Theofilis Visiting/Adjunct Professor since 08
  - Rodríguez visited in 08, will return in 09 (one month)
  - Joint publications in preparation with
    - Tumin (on characterization of eigenspectra)
    - Fasel (on global instability of 3d bubble flows)
- Stanford U
  - Joint publication in preparation with
    - Marxen (on laminar separation bubbles)
- U of Patras
  - Provision of 2d shock-induced laminar separated basic flows
  - Joint publication (IUTAM 2009) with
    - Ekaterinaris (on preliminary global instability analyses)