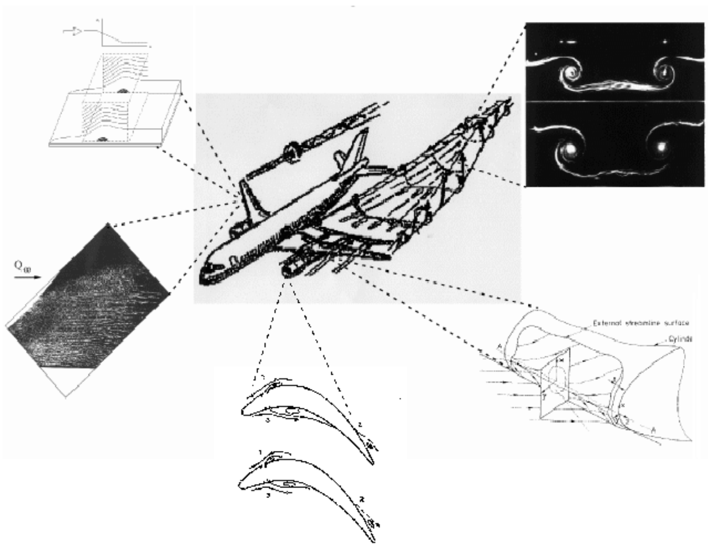
Global Flow Instability and Control III
Crete, Greece, Sept 27-30 2005



A synthesis of presentations

written by
V. Theofilis

based on notes provided by:
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1. Introduction

The third in the series of biennial symposia established in 2001 was held in Hersonissos, Crete, Greece, September 27-30, 2005, having as its primary objective the creation of a forum for presentation and discussion of results and open issues in global flow instability and control. Aspects of recent advances in theory, numerical algorithms, and experiment, were discussed, which enable identification and control of fluid flow global instabilities in real-world applications. The target audience encompassed active specialists who continue contributing to pioneering developments in this field and are willing to promote the synergy between theory, experiment and computation in order to advance both the frontiers of knowledge and technology transitions in this field. As planned by the Organizing Committee, topics discussed included:

- Global instability and control of flows, the basic state of which is inhomogeneous in two or all three spatial directions.
- Accurate and efficient algorithms for the numerical solution of large (partial-derivative) eigenvalue problems and direct numerical simulation. For the first time, attention was paid to next-generation PSE-3D and TriGlobal instability analysis concepts.
- Theoretical, computational, and experimental work on transient growth in such flows, and in particular the relation of transient growth to flow control.
- Experimental and computational investigations and demonstrations of open and closed-loop control.
- Flow control methodologies, including optimal control, adjoint-based methods, and reduced-order modelling. Applications included control of hydrodynamic and aeroacoustic instabilities.

A summary of all presentations, including comments made by the audience and responses given by the authors, is discussed next.

2. Presentations

2.1 Separation and Control (Day 1)

(Notes provided by R. W. Jefferies and J.D. Schmisseur; edited by V. Theofilis)

Gaster, in a combined theoretical and experimental invited presentation, introduced the subject of "Suppression of boundary layer instability by active control" focusing on the flat-plate boundary layer and exploitating linear stability theory to aid active flow control in an open loop manner. The simplest configuration discussed comprised one actuator and one upstream detector. Linear analysis in low Reynolds numbers indicated that closed loop control is also feasible, but requires more than one detector to separate near field from propagating wave. It was stressed that the minimum number of detectors and locations need be determined for three-dimensional flows, while two actuation modes (blowing/suction) were used to control flow and cancel disturbances. In addition it was proposed to exploit the beneficial effect of compliant surfaces on Tollmien-Schlichting instability by simulating compliance on rigid surfaces by use of arrays of sensors and actuators.

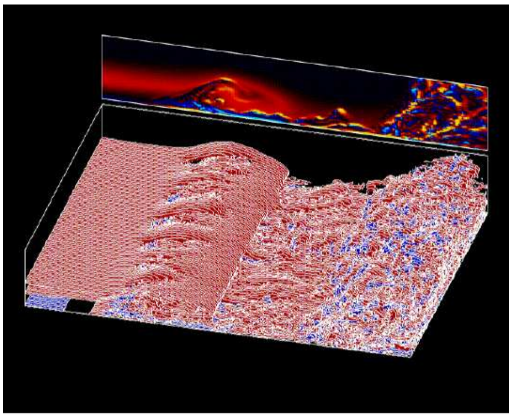

Figure 1. Visualization of instantaneous vorticity in the vicinity of the re-attachment zone of the laminar separation bubble, obtained by Direct Numerical Simulation (U. Rist 2005 "Absolute Secondary Instability in a Laminar Separation Bubble")

Rist used Direct Numerical Simulation (DNS) to discuss "Absolute Secondary Instability in a Laminar Separation Bubble". A snapshot of results presented in shown in Figure 1. The author demonstrated that self-sustained secondary instability of absolute nature may be detected at certain regions of parameter space, once the primary linear amplification has reached a finite-amplitude state, either via amplifiaction of two-dimensional or weakly three-dimensional waves. He went on to examine the effect that flow parameters such as pressure gradient, boundary layer thickness, amplitude of 2-D disturbance, bubble shape and bubble circulation have on the newly discovered mechanism.

Diwan and **Ramesh** presented experimental results "On the Primary Transition Mechanism of a Laminar Separation Bubble". They addressed the still open question of classification of laminar separation bubbles and the corresponding linear instability mechanisms they may sustain, in an effort to identify the dominant primary instability mechanism. The authors concluded that for such analysis to be possible forcing can only be introduced upstream of the separation bubble and that instability is due to velocity inflections of attached upstream boundary layer.

2.2 Toward Tri-Global Instability (Day 1)
(Notes provided by R. W. Jefferies and J.D. Schmisseur; edited by V. Theofilis)

Hall and Galionis discussed "Instability of slowly-varying 3-D flows" via solution of the spatial BiGlobal eigenvalue problem in a streamwise corner flow (Galionis & Hall 2005) and an extension of "classic" BiGlobal linear theory in a rectangular duct of varying aspect ratio, the latter under the assumption of the channel divergence being proportional to powers of an (inverse Reynolds number) small parameter. A key point of the latter analysis, which is a variant of the PSE-3D methodology, is the need to use non-linear theory in order to evaluate the basic states to be analyzed. Results have been published for the corner flows, while work is in progress in the divergent duct case.

Leriche and Labrosse presented the first TriGlobal instability analysis applied to the Stokes part of the equations of fluid motion, in a talk entitled "Stokes Eigenmodes in Confined Geometries". They discussed the scaling laws for the eigenvalues of the related operator, when the number of spatial directions treated as homogeneous decreased from (the analytically solvable problem of) three to the currently solved problem of three inhomogeneous spatial directions. Solution of the latter problem requires state-of-the-art numerical approaches (Leriche and Labrosse 2004). The authors showed that 2-D velocity-potential/vorticity correlations hold in 3-D and posed the (presently unanswered) question of potential relation of 3-D Stokes eigenmodes to the better understood modes resulting from proper orthogonal decomposition.

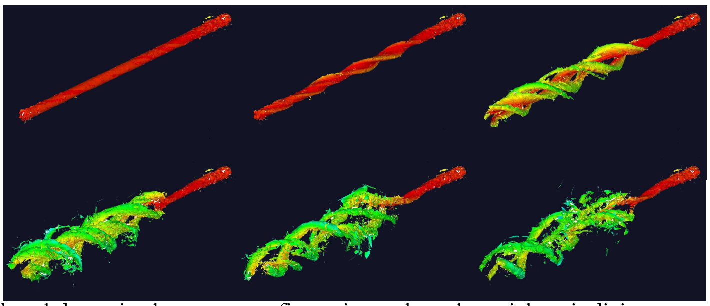

Figure 2. Vortex breakdown in the same configuration, when the axial periodicity assumption is relaxed. Results taken from M. Broadhurst, S. J. Sherwin and V. Theofilis 2005 "Vortex Stability and the Potential Application of the Parabolized Stability Equations".

Broadhurst, Sherwin and Theofilis discussed: "Vortex Stability and the Potential Application of the Parabolized Stability Equations". After presenting a summary of stability analysis techniques they demonstrated that BiGlobal analysis results of an isolated Batchelor vortex instability are consistent with those obtained by DNS calculations of development of small-amplitude disturbances. The point was made that axial velocity instability relates to vortex breakdown. An image of the disturbance amplitude function of the axial velocity perturbation is shown in Figure 2 (Broadhurst, Sherwin & Theofilis 2004). Further, the authors presented the formulation on which the classic PSE concept (as applied to boundary-layer type of flows, e.g. by Hall & Galionis and Hein herein) can be extended to study systems of vortices with mild variation in the axial and strong variaton on the radial and azimuthal spatial directions. Numerical analysis of the resulting PSE-3D system of equations was presented and the issue of validity of assumptions required to numerically model absolute and convective instability in this class of inhomogeneous flows was discussed.

2.3 Global Instability and Transient Growth

(Notes provided by J.D. Schmisseur and R. W. Jefferies; edited by V. Theofilis)

Glezer presented an invited talk entitled: "Virtual Surface Aerodynamic Flow Control: Coupling the Global Flow Instabilities" in which the coupling between trapped vortex flow control and global instabilities was discussed. He presented two flow control approaches which used the same momentum coefficients, namely Low Frequency (LF – receptivity based) and High Frequency (HF – stabilizing, more dissipative at higher frequencies). LF takes advantage of transient phenomena (transient-based control). Its limits of application are identified as being post stall and low angle of attack.

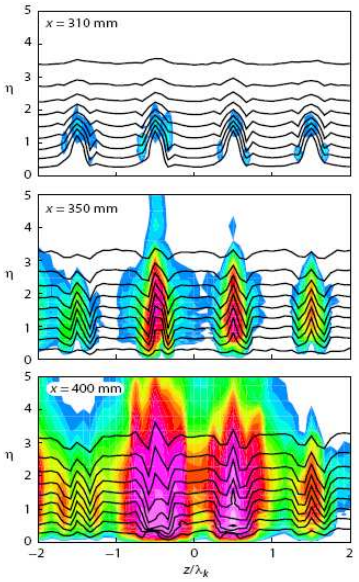

Figure 3. Isolines of experimentally recovered streamwise velocity, at roughness-based Re = 540 (White, Ergin & Gürün 2005 "Unsteady disturbance growth in boundary layers with stationary transient disturbances".)

White, Ergin and Gürün discussed "Unsteady Disturbance Growth in Boundary Layer with Stationary Transient Disturbances" on the basis of two experiments: roughness disturbances leading to bypass transition and Tollmien-Schlichting wave suppression using transient modes. They found that transition is the outcome of a race between roughness disturbance energy growth and a decaying base state. Specifically, although modulated T-S waves grow more slowly than their unmodulated counterparts, transition occurs sooner on account of the modified flow field.

Govindarajan and Sameen presented results on "Wall heating for transient growth control", where the effect of viscosity stratification in channel flow was investigated. Both linear and transient mechanisms were studied and it was shown that the usually employed stratification of viscosity in the direction normal to the wall, which has a stong influence on linear eigenmodes, has little impact on the transient growth mechanism. On the other hand, it was shown that a variable Prandtl number impacts transient growth stability, such that the impact of buoyancy on transient growth must be considered.

Hein discussed "High Resolution PSE of crossflow dominated transition", employing a well-resolved efficient numerical approach capable of capturing high frequency secondary disturbances, the latter being a precursor to transition on swept wings (Hein 2004). The approach employed is of the PSE-3D class, albeit considering the spanwise spatial direction as periodic., and is thus more restrictive than the approach discussed by Broadhurst *et al.* herein. Non-linear disturbance development allowed observation of disintegration of secondary disturbance structures. Nevertheless, it would be interesting to employ this approach to study the effects of varying angle-of-attack on disturbance behavior.

2.4 Numerical Approaches I (Day 2)

(Notes provided by H. Fasel and R. Joslin; edited by V. Theofilis)

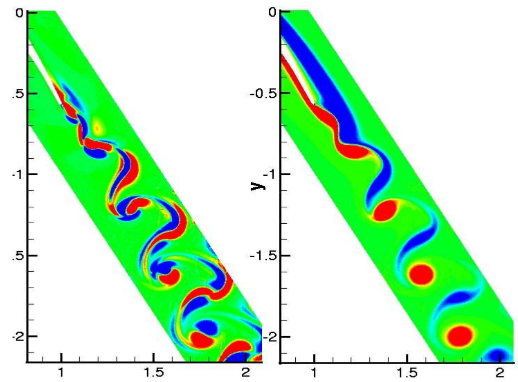

Figure 4. Amplitude function of disturbance vorticity (left) and corresponding time-periodic basic state (right) in the Floquet BiGlobal instability analysis of Abdessemed, Sherwin & Theofilis (2005) "Linear stability analysis of the flow past a low-pressure turbine blade".

Deville delivered an invited presentation, in which he posed and answered the question "What can spectral element methods bring to instability analysis?". He presented results for free surface waves, fluid-structure interaction, convection-diffusion-dominated, pulsatile, and viscoelastic flows at low Reynolds numbers. He argued that good numerics is essential for capturing flow physics and substantiated this by pointing to the absence of dissipation in the free surface waves calculation shown. Regarding details of a particular computation of his, the question whether pressure updates are required for each stage of time stepping was left unanswered. What is certain is that the cost of the spectral methods proposed scales with N^4 for an N^3 grid, N being the number of degrees of freedom utilized. The author argued that it is not necessary for the community to abandon their currently used numerical methods, although the spectral methods advocated should be incorporated as a preconditioning technique that would increase accuracy. On the other hand, for his base flow calculations the author himself did not use a spectral element method.

Abdessemed, Sherwin and Theofilis presented "Linear stability analysis of the flow past a low-pressure turbine blade" discussing primary and secondary linear instability analyses of flow past the T-106/300 low-pressure turbine (LPT) blade. Their BiGlobal instability results agreed with DNS results, while two previously unknown modes, termed "bubble" and "wake", respectively, were discovered in the 3D primary stability analysis (Abdessemed, Sherwin & Theofilis 2004). Secondary analysis was performed employing Floquet theory. Results were presented, describing neutral curves relative to stable short and unstable long wavelength primary modes; an eigenmode obtained is shown in Figure 4. The authors further used instability results for turbine blade to initialize 3D DNS. The latter agrees with Floquet theory; however, DNS results suggest mode-mode interactions, potentially pointing to transient growth. The onset of three-dimensionality was found to be close to critical Reynolds number.

In parallel, validation results were presented on the cylinder; it was unclear whether the (shedding) leading eigenmode recovered is related to varicose mode. At question time it was claimed by a participant that Tollmien-Schlichting waves and Görtler modes cannot be recovered using BiGlobal analysis, which the authors refuted, asserting that increasing resolution such modes could also be captured (e.g. see the work of Hoepffner *et al.* herein).

Sharma, Sherwin, Abdessemed and Limebeer presented a talk on "Transient growth of global modes in complex geometries", extending the previous work on the LPT blade. The concept extends classic transient growth analyses, invariably performed in channel and boundary-layer type of flows (Schmid & Henningson 2001). Transient growth in complex geometries can be studied by means of calculating the singular values of the matrix describing BiGlobal instability of the LPT flow which, in turn, can be calculated as an eigenvalue problem of a matrix combining the discretized and the adjoint BiGlobal eigenvalue problems. The method has been benchmarked in channel flow against Squire/Orr-Sommerfeld problem and excellent agreement with textbook results has been obtained. Preliminary results of a two-dimensional basic flow have been presented in the circular cylinder, while work is in progress in the LPT geometry. The authors refuted criticism from the audience, that using singular modes as a basis for transient growth studies may not be a good idea, by asserting that choosing as basis for the analysis one that spans both left and right singular vectors does indeed permit transient growth studies in complex geometries.

2.5 Numerical Approaches II (Day 2)

(Notes provided by H. Fasel and R. Joslin; edited by V. Theofilis)

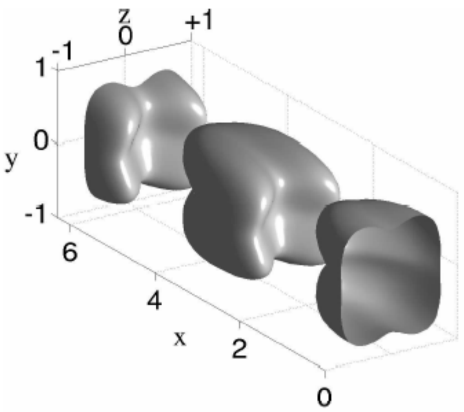

Figure 5. The most unstable eigenfunction in the square duct at Gr = 3000, Re = -400, Pr = 7 and streamwise wavenumber $\alpha = 1$, taken from Uhlmann & Nagata (2005) "Linear stability of duct flow with internal heating".

Uhlmann and Nagata discussed the linear stability of square duct flow with internal heating. Unlike the analogous problem without heating, solved by Tatsumi and Yoshimura (1990), it was found that the inflectional profile characteristics are important for impacting flow instability. Four symmetric modes were found to be possible, the most significant of which is presented in Figure 5 at a given set of parameters, giving rise to an unstable cone-like region for Pr > 0. These instability modes were found to be unrelated to those of Tatsumi. It was commented that the flow, in which the vanishing Pr limit corresponds to Gr getting large, may be particular to the rectangular duct (being introduced by the side-walls) and they may not be observable in the idealized plane channel case.

González and Gómez-Blanco presented a finite-element method for viscous incompressible BiGlobal linear instability analysis on unstructured meshes. They used 2D basic flows in the 3D time domain and presented results for rounded trailing edge thick flat plate (with rotating TE for wake control) and regularized cavity at low Reynolds number. Besides establishing accuracy of their results, the authors interacted with the audience to pose a series of questions relevant to the issue of global instability identification, such as the scope of use of finite-element methods for this type of problem, computing cost vs. benefit issues. These questions are, in turn, related with the number of nodes necessary for the resolution of a single wavelength. They asserted that, while the need for space and time convergence is paramount in any kind of computation, the goal of computing in the context of BiGlobal analysis – identification of instability characteristics – can be met by the approach presented.

Laxmi and **Gajjar** discussed global instability calculations using Chebyshev collocation and high-order (4^{th}) finite differences. The primary motivation of the authors was to study global instability in a supersonic compression ramp (Korolev, Gajjar & Ruban 2002). As a preliminary step they introduced incompressible and compressible approaches, based on continuation, for determining the steady base and unsteady flow in a streamfunction/vorticity formulation. The lid-driven cavity problem was used to test their approach and conduct grid resolution studies. Deville pointed out that the driven cavity problem is a mathematically ill-posed problem and should not be used as a proper test case, a statement that was further substantiated during the presentation by Robinet *et al.,* that dealt with the critical Reynolds number for the two-dimensional lid-driven cavity flow. Unsteady triple-deck equations were used for the compression ramp and an instability associated with separation bubble was detected; however, no BiGlobal analysis results were available for the workshop. As a precursor for the analyses, results for multiple adjacent cylinders were discussed, varying the gap width, and it was proposed that an absolute instability might cause a vortex disconnect. Again, the necessity for a baseline challenge problem, on which the community may work, was identified.

2.6 Flow Control (Day 2)

(Notes provided by A. Sharma and S. Sherwin; edited by V. Theofilis)

King, Seibold, Henning, Lehmann, Noack, Morzynski & Tadmor presented an invited talk on "Nonlinear and adaptive control of bluff body flows". Both passive and active flow control approaches were discussed, while active flow control was further subdivided into open loop and closed loop. It was argued that closed loop control is better on three counts, enhanced robustness, better disturbance rejection and higher efficiency in terms of control signal energy. An example was given for lift/drag ratio enhancement on a wing, where closed loop approach was shown to be superior. The authors also discussed the *Synthesis problem* – based on three approaches, (1) discretised full Navier – Stokes eqauations, (2) low order models of the Navier – Stokes equations and (3) system identification techniques to get black-box low order models. An example of low Reynolds number 2D flow past a cylinder was presented, where a full DNS description is available and the objective of flow control is to reproduce not only the stationary state (asymptotically reached in the computations) but also the transients in the path to that state. The *Modelling problem* included a Galerkin projection on 2D POD modes, which provides a low-dimension model. Introducing the so-called "shift" mode enhances dynamic convergence. Ultimately, introducing global eigenmode information proves essential to the reproduction of the transients. Finally, the *Control problem* seeks to stabilise shedding of the Kármán vortex street. Actuation could be provided either by cylinder transverse motion or by volume forcing (direct forcing in the Navier-Stokes equations in a volume), and the latter approach has been pursued. Techniques utilised have been the introduction of a harmonic solution to further simplify the reduced model, a coordinate transformation, in which Fourier coefficients (i.e. the temporal amplitude) translated to an amplitude and phase in the state space representation. A special feature of (approximation in) the problem, namely that the 'A' matrix is slowly time varying, permits to form the linear state-space model and seek to reduce the amplitude of oscillations as the control objective. A number of control strategies were explored, LPV, I/O linearization, proportional feedback etc. and in all cases it was asserted that, when available, phase information proved useful. Damping was lost after some time, meaning that the flow readjusts. This, in turn, is a result of the POD model being optimal for the field when unperturbed by control action or disturbance. A corollary of this finding is that models better suited for input-output sensitivity are needed. In future efforts adaptive control for the observer and estimation problems will be tried. Using the circular cylinder as a prototype bluff body configuration (experimentally) a drag reduction objective has been set. Since alternative vortices are shed, actuation at slot at edges is effected. In-phase actuation is effective, but actuation in antiphase is better. Again, the main conclusion is that phase information is important. In line with previously exposed ideas two approaches were tried, Approach 1, in which a low order model, having a time delay was identified. Synthesis of controller was tested in experiment and demonstrated good tracking and disturbance rejection. Approach 2 was also tested, employing an external seeking controller and activation on one side, and was found to performed equally well. (Noack, Afanasiev, Morzynski, Tadmor & Thiele 2003) In future efforts, the ideas exposed will be extended to three spatial dimension. A major challenge in that case is that the separation principle does not apply in nonlinear system, so estimation must be coupled to control.

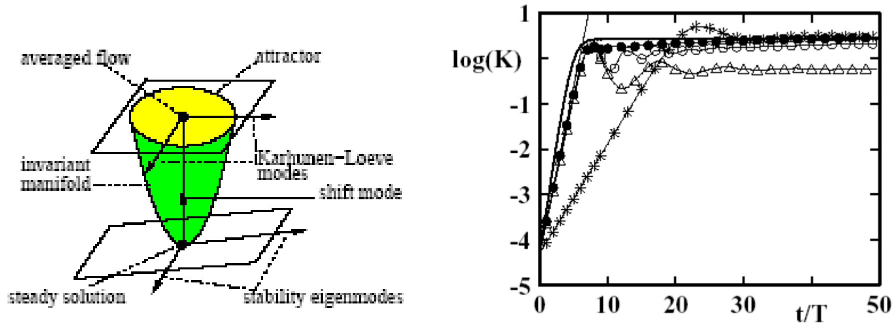

Figure 6. Left: Schematic representation of the ROM proposed by Morzynski, Stankiewicz, Noack, Lehmann, King, Thiele and Tadmor (2005) "Flow control design using global stability análisis and reduced order modeling". Right: the DNS data (solid) reproduced by a hierarchy of ROMs; best agreement obtained when BiGlobal information is injected into the model (closed symbols).

Morzynski, Stankiewicz, Noack, Lehmann, King, Thiele and Tadmor discussed "Flow control design using global stability analysis and reduced order modeling" and demonstrated the design of a flow control approach using global stability analysis and reduced order modelling. The authors contrasted active vs. passive control and concluded that active control performs better. From a theoretical point of view, they treated the linearized disturbance equations, leading to an eigenvalue problem. Their flow control strategy consisted in stabilization achieved via small perturbations introduced into the A matrix via small geometry perturbations (passive control) or via proportional feedback (active control). As a test geometry they chose flow past a cylinder, including a splitter plate (passive) or Strykowski wires (active). However, in the latter context the question arose as to the optimal placement of the wires. This was solved by monitoring the amplification rates of the BiGlobal eigenproblem consisting of the composite cylinder/wire geometry and changing the wire position until the amplification rates were minimized. The optimal placement of the wires was found to be at a location that, as Theofilis pointed out, could also be calculated (and has been calculated by Luchini in Crete II) by solution to the adjoint BiGlobal eigennvalue problem. Regarding the preferred active control approach, the authors commented that reduced order modelling is required and many options exist to construct such a model. These options largely fall into three categories, strictly mathematical, which is too large to be practically implemented, physics-based, which require intuition in addition to good knowledge of the problem at hand, and empirical, largely based on the Proper Orthogonal Decomposition. The chosen approach has been the latter, but it showed poor dynamic convergence, being optimal for the steady state only. An additional element, the so-called "shift mode" was added to the reduced-order model, making the latter stable and convergent. Finally, the addition of BiGlobal eigenmode information, produced a hybrid model that best reproduces both the DNS transients and the final stationary flow (Noack, Tadmor & Morzynski 2004). Nevertheless, the quest for improved models continues.

Hoepffner, Akervik, Ehrenstein and Henningson discussed "Control of instabilities in a cavity driven separated boundary layer flow", considering an open (micro-)cavity inside a boundary layer, basing the Reynolds number for their analysis on the displacement thickness of the boundary layer at inflow. They approached control from the point of view of the linearised BiGlobal disturbance equations in 2D flow. The basic state was calculated by DNS and the BiGlobal eigenmodes, akin to Tollmien.Schlohting waves on a curved surface (Ehrenstein & Gallaire 2005), were recovered by Arnoldi iteration. Eigenmode reduction was used and after identifying the most significant part of the eigenspectrum the authors constructed a model retaining 75 out of a total of 20000 eigenmodes. H_2 control of perturbations based on reduced model was performed, focusing on two types of modes, shear-layer- and bubble modes. Actuation and sensing placement was determined from the high energy regions in flow, after solving the adjoint BiGlobal eigenproblem. Injection of specific disturbance was also tested and a good rejection of specific disturbance was demonstrated. Regarding whether there exist more optimal methods of model reduction in terms of dynamic system response, the authors pointed that this issue relates to the low order modelling problem. Nevertheless, while some noise was included in the problem and reasonable actuation energies were recovered, it was again stated that global eigenmodes can be used for model reduction in this type of problem.

2.7 Numerical Approaches III (Day 3)

(Notes provided by H. Fasel and R. Joslin; edited by V. Theofilis)

Fasel, Postl and Gross presented an invited talk on "Instability and control of laminar separation bubbles: direct numerical simulations". The authors showed convective, absolute, and secondary (convective and absolute) instability mechanisms in 2D and 3D for a generic separation bubble on a flat plate, as well as one formed in the trailing edge separation region of the Pak-B Low Pressure Turbine (LPT) blade. They argued that bubble "shedding" is not necessarily a consequence of absolute/global instability, rather may be seen as "finite-amplitude Tollmien-Schlichting waves". They explained fundamental mechanisms of LPT separation control using Vortex Generator Jets (VGJs; Sondergaard, Bons & Rivir 2002), that were found to be different for steady or pulsed jets. Preliminary results demonstrated that closed loop control is beneficial to controlling the LPT flow. In response to the question from the audience as to the origin of the shed vortices, they reiterated that caution must be used with the term "vortices", since the phenomenon is one of large amplitude instability waves, primarily due to the shear layer instability. Gaster qualified the work as excellent and posed the rhetoric question "why do folks say that I did not understand the bubble instability physics?". Fasel responded that "true" instability, in Gaster's terminology of half a century ago, has recently been renamed "absolute" instability. A question raised, whether it is possible that the duty cycle influences the resulting frequency spectrum, received an affirmative answer. A further question was posed, whether it was known how long the absolute instability lasts in time before it becomes convective; this remains presently unknown. Regarding whether the amplitude of the unsteady aerodynamic forces is reduced after control, the answer was that there is a significantl reduction. It was finally stated that local stability analyses have not been performed to-date in this context.

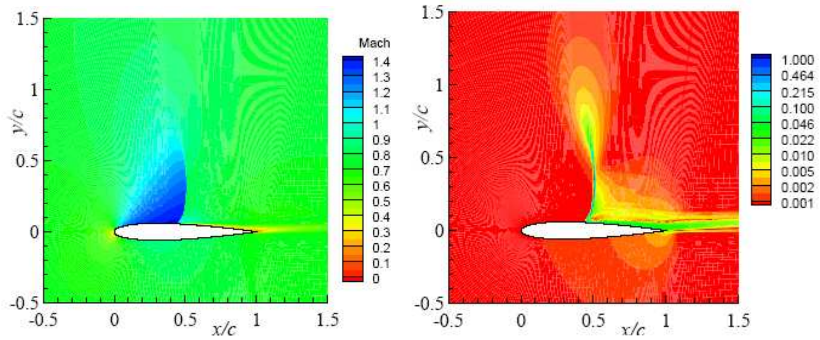

Figure 7. Left: Mach number contours for the flow around a NACA 0012 airfoil. Right: Streamwise disturbance velocity component pertinent to the most unstable eigenmode. Results taken from Crouch, Garbaruk & Magidov (2005) "Predicting the onset of flow unsteadiness using global stability theory".

Crouch, Garbaruk and Magidov introduced a method for "Predicting the onset of flow unsteadiness using global-stability theory", as applied to unsteadiness and the resulting structural buffeting for aircraft wings. As a model they analyzed a NACA0012 airfoil at an angle of attach and at flight Reynolds numbers. Experimental evidence points to a strong effect of Mach number on the onset of flow unsteadiness. For the analysis, Reynolds Averaged Navier-Stokes computations were used to obtain the base flow for BiGlobal analysis in compressible flow, including a shock wave. **The 2D BiGlobal analysis approach is the first of its kind in that it uses a turbulent mean, as opposed to a laminar steady basic state,** and was validated on a circular cylinder, where subcritical and critical flows were recovered and the critical Reynolds number predicted agreed with experiments; however the frequency of oscillations was under-predicted except at the critical Reynolds number. Subsequently, the approach was applied to the NACA0012 airfoil at transonic conditions, such that shock smoothing was required for the analysis. The effect of shock smoothing on the eigenvalue problem results was examined and found to be insignificant with respect to the prediction of critical conditions for buffet onset. The analysis suggests that the shock/shear layer modulation occurs in a "rocking" fashion, "rocking" presumably being a strongly coupled oscillation of the shock and the downstream shear-layer and wake. The BiGlobal instability analysis results agree well with the experiments at lower transonic Mach numbers but then deviate near Mach=0.8. The authors attributed the latter to either of two factors, namely the potential appearance and stronger amplification of three-dimensional modes or, simply, the difficulties in obtaining reliable experimental data at these conditions. Finally, it was stated that no acoustic modes were observed as yet.

Robinet, Gloerfelt and Corre presented the "Dynamics of two-dimensional square lid-driven cavity at high Reynolds number". They used DNS and the BiGlobal approach to study the same problem also addressed by Laxmi and Gajjar, namely prediction of the critical Reynolds number in the 2D flow, Re_{2D}. Although this is a somewhat academic question, since Theofilis (2000) has predicted that this flow becomes unstable to three dimensional perturbations at a Reynolds number an order-of-magnitude smaller than Re_{2D}, it exemplifies the need for accurate numerical approaches in order to arrive at reliable BiGlobal analysis predictions. The basic state was computed by a finite difference, semi-implicit Crank Nicolson scheme for the viscous terms and an Adams-Bashforth scheme for the convective terms. The corner singularities were attempted to be removed by use of known asymptotic solutions. Spectral collocation was used for the BiGlobal analysis. The basic flow was defined either as (a) the laminar steady or (b) the mean unsteady flow. The critical Reynolds number for amplification of two-dimensional disturbances was established in case (a), while work is in progress in case (b). This work raised again the question whether the basic flow can be computed beyond the first bifurcation and the consensus in the audience was that at some stage "the physics would fight back" (Fasel, referring to an earlier comment by Crouch). Theofilis suggested using his "residuals algorithm" (EOARD-supported work) to substantially shorten the length in the DNS of the time-integration subcritically, while Fasel reminded the audience that an accurate method based on arc-length continuation exists, due to Keller, that permits computing basic states beyond several bifurcations. Incidentally, this is the method used by Gajjar in his computations. Finally, Deville questioned the use of a staggered grid, since in that case artificial viscosity is required to keep the numerics stable and this may well influence the accuracy of the critical Reynolds number computation; in Deville's words "numerics matter".

De Vicente, González, Valero and Theofilis introduced "Spectral Multi-Domain Methods for BiGlobal Instability Analysis of Complex Flows over Open Cavity Configurations", presenting the first ever multidomain algorithm for the solution of the BiGlobal EVP in flows over complex geometries, that are decomposable into regular subdomains. Given firstly the sensitivity of EVP solutions to the details of the basic flow analyzed and secondly the relevance of stores to the open cavity problem, the solution approach aims at extending the scope of present open cavity analyses to address more realistic configurations. The basic flows have been computed using finite elements, while a detailed discussion of a solution algorithm for the EVP was presented. The authors discussed the relevance of the boundary conditions and domain interfaces and validated their approach using the Orr-Sommerfeld equation, analytically known two-dimensional eigenvalue problems and previous BiGlobal single domain results in the lid-driven cavity. Preliminary results for the standard L/D=2 open cavity and the same configuration in the presence of a "T" store model were presented, which document the large influence that stores have on the instability characteristics of the cavity.

2.8 Computational Aeroacoustics (Day 3)
(Notes provided by E. White; edited by V. Theofilis)

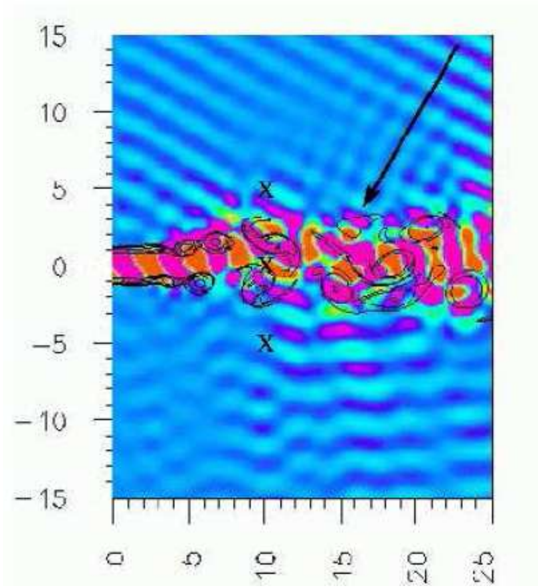

Figure 6. Quantification of scattering in the jet noise control theoretical work of Cerviño and Bewley (2005) "Techniques for the optimization and control of large-scale systems with application to jet noise".

Cerviño and Bewley discussed "Techniques for the optimization and control of large-scale systems with application to jet noise". They performed adjoint analyses of flow acoustics interactions in a 2D jet, in order to apply low-frequency control and reduce far-field noise. They demonstrated that the location of the actuators could be determined with this approach. Preliminary, yet unsatisfactory, optimization results were shown. A possible solution of the modest reduction of acoustic energy achieved may be the performance of a time periodic optimization. However, this approach requires time-periodic orbits, which are a challenge to identify in a large dimensional system.

Hein, Hohage, Koch and Schoerbel introduced "Acoustic resonances in a 2D high-lift configuration" by producing numerical solutions of a 2D Helmholtz eigenvalue problem. The analysis intended to identify possible connections between acoustics resonance and tonal flow noise in a complex high-lift configuration, in the absence of flow; the latter assumption is equivalent to accepting that the frequencies of the acoustic resonance are mainly determined by the geometry. The same configuration is examined from the point of view of acoustics experimentally. A high order finite-element approach was used (polynomial order $p < 14$) in combination with a Perfectly Matched Layer (PML) technique. Results were shown to be independent of the PML, while slat cove resonances and low-frequency surface wave resonances were identified in the analysis and were found to be a function of the geometry. The predicted frequencies were in qualitative agreement with strong tones found experimentally.

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3rd Global Flow Instability and Control Symposium

Final Schedule

Tuesday, September 27

07:30-08:00	**Registration**	
08:00-08:30	**Opening – Introductions**	
08:30-09:30	**M. Gaster [20] (Invited)**	Suppression of boundary layer instability by active control
09.30-10.00	**U. Rist [26]**	Absolute Secondary Instability in a laminar separation bubble
10.00-10:30	**S.S. Diwan [13] and O. N. Ramesh [13]**	On the primary transition mechanism of a Laminar Separation Bubble
10.30-11.00	**Coffee Break**	
11.00-11.30	**P. Hall [12]**	Instability of slowly-varying three-dimensional flows
11.30-12.00	**E. Leriche [6] and G. Labrosse [31]**	Stokes eigenmodes in confined geometries
12.00-12.30	**M. Broadhurst [12], S. J. Sherwin [12] and V. Theofilis [32]**	Vortex stability and the potential application of the Parabolised Stability Equations
12:30-14:30	**Lunch Break**	
14:30-15:30	**A. Glezer [10] (Invited)**	Virtual Surface Aerodynamic Flow Control: Coupling the Global Flow Instabilities
15:30-16:00	**E. B. White [3], F. G. Ergin [3] and A. M. Gürün [3]**	Unsteady disturbance growth in boundary layers with stationary transient disturbances
16:00-16:30	**R. Govindarajan [13] and A. Sameen [13]**	Wall heating as a flow control option for transient growth
16:30-17:00	**S. Hein [5]**	High-resolution PSE analysis of crossflow-dominated transition scenarios
17:00-19:00	**Dinner Break**	
19:00-21:00	**Discussion Groups**	

Thursday, September 29

08:30-09:30	**M. Deville [6] (Invited)**	What can spectral element methods bring to global instability analysis?
09.30-10.00	**N. Abdessemed [12], S. Sherwin [12] and V. Theofilis [32]**	Linear stability analysis of the flow past a low-pressure turbine blade
10.00-10:30	**A. Sharma [12], S. Sherwin [12], N. Abdessemed [12] and D. J. N. Limebeer [12]**	Global Modes of Flows in Complex Geometries
10.30-11.00	***Coffee Break***	
11.00-11.30	**M. Uhlmann [4] and M. Nagata [28]**	Linear stability of duct flow with internal heating
11.30-12.00	**L. González [33] and R. Gómez-Blanco [32]**	A finite-element method for viscous incompressible BiGlobal linear instability analysis on unstructured meshes
12.00-12.30	**B. V. B. Laxmi [29] and J. S. B. Gajjar [29]**	Global instability calculations using Chebychev collocation and high-order finite differences
12:30-14:30	**Lunch Break**	
14:30-15:30	**R. King [22], M. Seibold [22], L. Henning [22], O. Lehmann [22], B. R. Noack [22], M. Morzynski [19] and G. Tadmor [17] (invited)**	Nonlinear and adaptive control of bluff body flows
15:30-16:00	**M. Morzynski [19], W. Stankiewicz [19], B. R. Noack [22], O. Lehmann [22], R. King [22], F. Thiele [22] and G. Tadmor [17]**	Flow control design using global stability analysis and reduced order modelling
16:00-16:30	**J. Høpffner [14], E. Åkervik [14] , U. Ehrenstein [30], and D. S. Henningson [14]**	Control of instabilities in a cavity-driven separated boundary-layer flow
17:00-19:00	**Discussion Groups**	
20:00-22:00	**Conference Dinner**	

Friday, September 30

08:30-09:30	**H. Fasel [25] (Invited)**	Instability and Control of Laminar Separation Bubbles: Direct Numerical Simulations
09.30-10.00	**J. D. Crouch [2], A. Garbaruk [21] and D. Magidov [21]**	Predicting the onset of flow unsteadiness using global stability theory
10.00-10:30	**J.-Ch. Robinet [7], X. Gloerfet [7] and Ch. Corre [7]**	Dynamics of two-dimensional square lid-driven cavity at high Reynolds number
10:30-11:00	**J. de Vicente [32], E. Valero [32] and V. Theofilis [32]**	Global instability of realistic open cavity flows
11.00-11.30	**Coffee Break**	
11.30-12.00	**L. I. Cerviño [34] and T. R. Bewley [27]**	Techniques for the optimization and control of large-scale systems with application to jet noise
12.00-12.30	**S. Hein [5], T. Hohage [11], W. Koch [5] and J. Schöberl [16]**	Acoustic Resonances in a 2D High Lift Configuration

13:00-15:00	**Lunch Break**
15:00-17:00	**Discussion Groups**
17:00-19:00	**Presentations and Synthesis**
19:00-19:30	**Closing Remarks – Meeting Adjourns**

Observers

R. W. Jefferies [1] , R. D. Joslin [17] , J. D. Schmisseur [1] , J. Sesterhenn [23] , S. J. Sherwin [12] , S. Surampudi [8]

Affiliations

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5	DLR, German Aerospace Center	Göttingen	Germany
6	Ecole Polytechnique Federale de Lausanne	Lausanne	Switzerland
7	ENSAM	Paris	France
8	European Office of Aerospace Research and Development	London	United Kingdom
9	FOI, Swedish Defense Research Agency	Stockholm	Sweden
10	Georgia Tech	Atlanta, GA	United States
11	Georg-August-University Göttingen,	Göttingen	Germany
12	Imperial College London	London	United Kingdom
13	Indian Institute of Science	Bangalore	India
14	KTH, Royal Institute of Technology	Stockholm	Sweden
15	Jawaharlal Nehru Center for Advanced Scientific Research	Bangalore	India
16	Johannes Kepler University	Linz	Austria
17	Northeastern University	Boston, MA	United States
18	Office of Naval Research	Washington, DC	United States
19	Poznán University of Technology	Poznán	Poland
20	Queen Mary College	London	United Kingdom
21	Saint-Petersburg University	Saint-Petersburg	Russia
22	Technical University Berlin	Berlin	Germany
23	Technical University Munich	Garching	Germany
24	Tel Aviv University	Tel Aviv	Israel
25	University of Arizona	Tucson, AZ	United Status
26	University of Stuttgart	Stuttgart	Germany
27	University of California, San Diego	San Diego, CA	United States
28	University of Kyoto	Kyoto	Japan
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33	Universidad Pontificia de Comillas	Madrid	Spain
34	University of Sevilla	Sevilla	Spain

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Standing, left-to-right: H. Fasel, J.D.Schmisseur, J. Gajjar, M. Gaster, R. King, M. Broadhurst, N. Abdessemed, L. González, J. de Vicente, J.-Ch. Robinet, E. Leriche, M. Morzynski, S. Hein, U. Rist, M. Deville, O.N. Ramesh, R. Joslin, R.W. Jefferies, J.D. Crouch, V. Theofilis, S.J. Sherwin.
Sitting, left-to-right: L. Cerviño, J. Sesterhenn, J. Hoepffner, A. Sharma, R. Govindarajan