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Dynamics of localized disturbances in engineering flows: a report on Euromech Colloquium 353

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Euromech Colloquium 353, held at the University of Karlsruhe, Germany, 1–3 April 1996 brought together scientists working in the field of localized disturbances of flows in order to discuss new developments and the potential for application. The colloquium attracted a total of 56 participants from nine European countries, i.e. France, Germany, The Netherlands, Poland, Russia, Sweden, Switzerland, Ukraine and United Kingdom as well as from the US and Israel.

1. Introduction

Any realistic disturbance in a flow field is of limited spatial extent. During the last 10–15 years considerable progress has been made in the understanding of the physics of locally excited disturbances in unstable flows. Theoretical, experimental and numerical work has contributed to this progress. First, the aim of the colloquium was to summarize the state of the art knowledge in the field of wave packet dynamics including the three-dimensional, compressible, and non-parallel linear theory and extensions to nonlinearity as well as experiments and numerical simulation. Further the colloquium was intended to show how the developed theory of localized disturbances can be used in applied engineering problems. The role these disturbances play in the framework of transition to turbulence, active flow control etc. were to be discussed.

2. Report on presentations

Although restricted to the frame of engineering flows (as opposed to e.g. the field of geophysical flows) papers were presented from a wide range of topics related to localized disturbances. Theoretical, numerical and experimental investigations were dealt with, which contributed to the insight into the complex phenomena involved. The presentations may be subdivided into five sections: Disturbance initiation, Unstable three-dimensional boundary layers, Role of longitudinal flow structures, Convective, absolute and global instabilities, and Miscellaneous topics in localized disturbance studies.

2.1. *Disturbance initiation and implications*

New promising analytical as well as numerical approaches to the description of the crucial disturbance initiation process due to localized roughness or wall suction/ blowing were presented. Several different disturbance initiation scenarios (wall slot suction, local steady and unsteady two-dimensional surface bumps) in the zero pressure gradient boundary layer were discussed, applying linear theory and parallel flow assumption. The disturbance field was described as a Fourier integral over the wave-eigenforms of the Orr–Sommerfeld problem for fixed frequency and compares well with experiments even for relatively large values of the flow disturbances (Gaster, Queen Mary & Westfield College, London, UK). The evolution of disturbances evolving due to a three-dimensional time-harmonic point source in an adverse pressure gradient boundary layer showed a pronounced effect of the excitation frequency on the three-dimensional structure of the resulting wave train (Michalke & Neemann, Technische Universität Berlin, Germany). The receptivity process due to an isolated roughness element in a three-dimensional, non-parallel boundary layer was investigated using WKB theory. The actual roughness geometry is replaced by a spectrum of slowly varying functions which produce the proper far-field disturbance (Bertolotti, DLR Göttingen, Germany).

It could be shown experimentally that the orientation and phase of an initial pulse disturbance plays an important role in the nonlinear regime of the disturbance evolution (Medeiros & Gaster*, Cambridge University, UK, *Queen Mary & Westfield College, London, UK). A wave resonance phenomenon was found theoretically between unstable and stable disturbance eigenmodes of a boundary layer flow, leading to early nonlinear interaction. Very large differences in disturbance evolution may result, depending on the phase relation among the spectral components of the excitation signal (J. Healey, Brunel University, Uxbridge, UK).

2.2. *Unstable three-dimensional boundary layers*

The problem of the evolution of disturbances in flows which are unstable to the crossflow instability (CFI) was intensely discussed. This case is of particular interest for the laminar flow technology of swept wings as used in commercial aircraft. The traditional N-factor prediction method for the laminar–turbulent transition was heavily criticized for being unable to describe the mechanisms responsible for the breakdown of the laminar flow.

The important experimental observations (reported by Bippes, DLR Göttingen, Germany and Saric, Reibert & Radeztsky Jr, Arizona State University, Tempe, USA) may be summarized as follows. (i) The unsteady disturbance modes of CFI are receptible mainly to free-stream turbulence (FST), but not to sound. (ii) The steady modes are strongly receptible to roughness and dominate at low and moderate FST level, even for extremely smooth surfaces. Because of the significance of steady crossflow vortices in saturated state, nonlinear finite-amplitude solutions have been computed (Koch, DLR Göttingen, Germany). (iii) In combination, the steady modes are attenuated by unsteady modes, i.e. low and moderate FST levels delay the transition dominated by stationary mode disturbances. (iv) The occurrence of local high-frequency disturbances following the saturation of the amplitudes of crossflow vortices is crucial for the final breakdown process. (v) The influence of roughness on transition appears to be especially pronounced for roughnesses placed within a distance of 2–5% of the chord length from the attachment line. (vi) Isolated roughness elements generate a longitudinal vortex and accompanying co-vortices, leading to an early, localized transition downstream.

An absolute instability was found theoretically as well as experimentally in the rotating disk flow which appears to be similar to the swept wing three-dimensional boundary layer flow (Lingwood, University of Cambridge, UK). The change from convective to absolute character of the instability occurs as a Reynolds number effect (critical radius for given rotation speed). The question remains to be answered of whether the rotating disk findings can be transferred to the swept wing flow.

2.3. *Role of longitudinal flow structures*

The significance of longitudinal flow structures for changes in the evolution of laminar and turbulent flows was underlined by many contributions The following important aspects were discussed. (i) Longitudinal, long-lived flow structures can be created in a boundary layer by three-dimensional (i.e. localized) disturbers and are essential in obtaining considerable heat transfer enhancement (Yurchenko, National Academy of Sciences of Ukraine, Kiev, Ukraine). (ii) Localized 'streaky' structures apparently play a crucial role in the generation of turbulent spots by interaction with Tollmien–Schlichting instabilities (TSI). It is this very interaction process which could serve as a model for the mechanism of the influence of FST on bypass transition in two-dimensional boundary layers (Kozlov, Russian Academy of Sciences, Novosibirsk, Russia). Here, the presence of an additional perturbation spectrum (e.g. TS waves or free-stream disturbances at the boundary layer edge) is essential since isolated streaky structures could experimentally be shown to decay downstream (Westin, Alfredsson, Bakchinov[*] & Kozlov[*], Royal Institute of Technology, Stockholm, Sweden, [*]Russian Academy of Sciences, Novosibirsk, Russia). (iii) As a result of direct numerical simulations (DNS) localized longitudinal structures could be identified which originate through an algebraic growth process from localized small and finite amplitude initial disturbance amplitudes. Breakdown to turbulence appears to be associated with the rear part of the longitudinal structures (Henningson, FFA, Bromma, Sweden). (iv) Pronounced longitudinal structures were observed within turbulent spots in Couette flow, and identified as pairs of streamwise vortices. By introducing local stationary disturbances similar vortices can be generated, whose destabilization leads to turbulence (Bottin, Dauchot & Daviaud, CEA Centre d'Etude de Saclay, Gif-sur-Yvette, France). Streamwisely localized longitudinal structures in Couette flow were also found theoretically as unstable three-dimensional secondary eigensolutions of two-dimensional solitary-like nonlinear equilibrium states (Cherhabili & Ehrenstein, Université Lille 1, Villeneuve d'Ascq, France). An exact steady solution of the compressible Navier–Stokes equations has been reported for Couette flow, making it specially amenable to theoretical perturbation studies. There exists a linear instability characteristic for supersonic Couette flow, enabling the classical multi-stage transition process, starting from small disturbances, which has been simulated directly (Stoynov, Russian Academy of Sciences, Moscow, Russia). Therefore, the significance of longitudinal structures in the understanding of transition in Couette flow seems less pronounced in compressible Couette flow.

2.4. *Convective, absolute and global instabilities*

The contributions from the sub-field of absolute/convective and global instability theory emphasized the following items. (i) The enhancement of the concept of absolute instability to global instability shows that the interplay of local absolute growth rate and non-parallelism can be crucial for an actual occurrence of self-excited flow oscillations. Extension of the concept to weakly nonlinear disturbance evolution was discussed and successfully applied in situations far from critical. Various vortex shedding scenarios behind cylinders could be described. Further, an actual design of flow control in low Reynolds number flows seems feasible as exemplified by vortex shedding suppression (Monkewitz, Swiss Federal Institute of Technology Lausanne, Switzerland). (ii) The dynamics of wave packets can be correctly simulated with vortex blob methods (and their extensions to incorporate viscosity), additionally providing for the possibility of investigating nonlinearity, especially large initial disturbances and strongly non-parallel flow effects (Ehrhard, Delfs* & Meiburg**, University of Karlsruhe, Germany, *DLR Braunschweig, Germany, **University of Southern California, Los Angeles, USA). (iii) Global instabilities do not always lead to better mixing of jet flows. (iv) The controlled (one-sided) initiation of global instabilities may be used to redirect jets without moving mechanical parts (Strykowski, University of Minnesota, Minneapolis, USA). (v) In the case of significance of surface tension a liquid jet can either be convectively or absolutely unstable, which profoundly determines the way in which its breakup into drops takes place. Although temporal instability of a jet with magnetic permeability decreases with increasing strength of an axially oriented magnetic field, the domain of absolute instability may grow (Yakubenko & Shugai, Royal Institute of Technology, Stockholm, Sweden). Thus a control of liquid jet breakdown appears to be describable by means of absolute instability theory (application: jet printer). (vi) Absolute instability was found computationally in an axisymmetric supersonic wake flow (Leopold & Augenstein, ISL, Saint-Louis, France). (vii) Using DNS of the linearized Navier–Stokes equations the Batchelor vortex was investigated with respect to absolute/convective instability. The study revealed that moderate swirl strongly promotes absolute instabilities of pure jets and wakes (Delbende, Chomaz & Huerre, Ecole Polytechnique, Palaiseau, France).

2.5. *Miscellaneous topics in localized disturbance studies*

The downstream evolution of wave trains and turbulent spots were addressed by a number of speakers. Experimental investigations of the evolution and breakdown of a wave train, excited by a harmonic (suction/blowing) point source showed that classical transition scenarios are observed within the wedge-like region downstream of the disturbance initiation, up to the formation of Λ-vortices (Wiegand, Besteck, Wagner & Fasel*, University of Stuttgart, Germany, *University of Arizona, Tucson, USA). In a similar investigation the growth characteristics of pointwise, harmonically excited disturbances where determined and found to agree well with primary instability theory (Seifert & Tumin, Tel-Aviv University, Ramat-Aviv, Israel). The lateral spreading of a wave packet in a subsonic boundary layer decreases with increasing Mach number while simultaneously the packet's content of three-dimensional disturbance components increases considerably (Delfs, DLR Braunschweig, Germany). It was shown experimentally that, compared to the zero pressure gradient boundary layer, an adverse pressure gradient considerably enhances the streamwise and spanwise growth of a turbulent spot (van Hest, Nentjes & Passchier, Delft University of Technology, The Netherlands).

The following additional items on flow control and instability were reported. (i) Acoustic feedback from a localized actuator, placed downstream of an airfoil at free-stream Mach number 0.7 was effectively used to control buffeting or separation respectively (Szumowski & Meier, Warsaw University of Technology, Poland, *DLR Göttingen, Germany). (ii) Local acoustic excitation of well-defined vortical coherent structures in a turbulent jet enabled the distinction of random and organized vorticity fluctuations using phase-averaging techniques. The study revealed that the organized vorticity due to coherent structures plays the double role of increasing directly the radial heat transfer as well as increasing the production of random vorticity, which is phase related to the structures (Drobniak, Elsner & El-Sayed Abou-El-Kassem*, Technical University of Czestochowa, Czestochowa, Poland, *Cairo University, Giza, Egypt). (iii) The control of mixing efficiency of a jet was studied systematically by initiation of vortex rings under various conditions (Nikishov & Oleksiuk, National Academy of Sciences of Ukraine, Kiev, Ukraine). (iv) Effects of localized and distributed buoyancy forces on receptivity of boundary layer flows were formalized and characterized by basic flow parameters (Nikiforovich, National Academy of Sciences of Ukraine, Kiev, Ukraine). (v) The influence of microdispersed particles on stability characteristics was discussed theoretically (Chernyshev, Volgograd State University, Volgograd, Russia).

3. Conclusions

The presentations showed that the application of the knowledge acquired in the field of localized flow disturbances is just about to start. Several examples of such applications in engineering flows, e.g. modelling of surface roughness, locally introduced disturbances for heat transfer enhancement, one-sided excitation of instabilities for re-direction of jets, description and control of breakdown of ink jets, etc. have been reported and intensely discussed. Many contributions showed that often the observed disturbance growth phenomena in flows can be understood only because of their localized character and not by means of classical wave instability theory. The colloquium indicated again the potential but also the need for further research into means of application of localized disturbances especially in laminar flow technology and active flow control.

Details of all the presentations given at the colloquium are documented in a booklet of summaries. This booklet *Dynamics of localized disturbances in engineering flows* is available from either of the authors. A list of the contributions is given in the references.

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