Discussion meeting on instability and transition in fluid flows – A report

A discussion meeting on instability and transition in fluid flows was organised by R. Narasimha under the auspices of the Indian Academy of Sciences, during 22–25 November 1996. About twenty-five participants gathered at Orange County resort, in the idyllic setting of Coorg, characterized by its hilly terrain, deep green forests and plantations, and located near the banks of the river Cauvery. The sessions were designed so as to have invited lectures by many of the participants, followed by discussion and question/answer sessions after each talk.

The meeting was mainly intended to get together Indian researchers working in the field of instability and transition. Michael Gaster and Jitesh S. B. Gajjar, both from the United Kingdom and at that time academic visitors at the Jawaharlal Nehru Centre for Advanced Scientific Research and the Indian Institute of Science, Bangalore, also participated in the meeting.

While the subject of Instability and Transition may seem very specialized, this is quite a broad area in the field of fluid mechanics, and it was not the objective of the meeting to concentrate on any focussed topic; rather, the objective was basically to look at each others' work, and thereafter to look at common themes or possible common future endeavours. Towards both these objectives the meeting proved to be a success, and was very valuable to the participants. It will therefore be best to report briefly on the talks that were presented, and later on to look at what seemed to emerge as possible common endeavours of enquiry.

Rama Govindarajan of National Aerospace Laboratories, Bangalore, spoke on 'Low order theories for stability of non-parallel boundary layer flows'. Essentially the objective of the work was to take a re-look at the full non-parallel equation for boundary layer flow, and decide on which were the most important (in some sense) terms that needed to be retained. The terms retained are the following. First, the Rayleigh operator; secondly, *only* the $(1/R_e)D^4\phi$ term from amongst the viscous group of terms in the classical Orr–Sommerfeld equation; and thirdly, in order to include the effects of non-parallelism, *only* the term $p\Phi D^3\phi$ from amongst the non-parallel group of terms. In the above, Φ and ϕ are respectively the mean-flow and perturbation stream-functios $D = d/dy$ with y as the co-ordinate normal to the plate, R_e is the Reynolds number of flow, and p is a co-ordinate scaling factor. Notable amongst the terms rejected is the explicit $\partial\phi/\partial x$ term (x being the streamwise co-ordinate); and thus, the governing equation becomes an ordinary differential equation. The rationale for rejection of the various terms is based on two arguments. First there is an asymptotic justification for the terms rejected as these are of higher order than the terms retained. Second, the mean-flow would have to be known to a higher order if the additional terms were to be kept. Rama presented numerical results to support her claim, and the results did seem to support her contention. Sen pointed out that the rejection of the $\partial\phi/\partial x$ term was consistent with Sen's concept of optimal normalization.

P. K. Sen of the Indian Institute of Technology, Delhi, spoke on 'Non-classical solutions of the boundary layer stability problem', based on work done with M. D. Thomas. Sen reviewed the classical outer boundary conditions for this problem, viz. $\phi \sim \exp(-\alpha y)$, where ϕ is the disturbance streamfunction, α is the spatial wave number, and y is the co-ordinate normal to the plate. He went on to show the uniqueness of the classical solution, basing his arguments on the method of adjoints. Regarding non-classical solutions, his main contentions were as follows. In the event that an Orr–Sommerfeld like equation $L(\alpha)\phi = 0$ is augmented by an ε-order term, and the equation is modified to $L(\alpha)\phi = \varepsilon L_2\phi$, where L_2 is a linear operator; then, it is possible to obtain a non-classical 'secular like' solution in the following manner. First, expand ϕ as $\phi = \phi_e + \varepsilon\phi_n$, where ϕ_e satisfies $L(\alpha)\phi_e = 0$, and ϕ_n satisfies $L(\alpha)\phi_n = \varepsilon L_2\phi_e$. However the outer boundary condition for the equation for ϕ_n is the *secular like* condition $\phi_n \sim y\exp(-\alpha y)$. This composite solution for ϕ is the non-classical solution, since two parts of ϕ, viz. ϕ_e and ϕ_n, have different manners of decay in the outer region. The net outcome of the non-classical solution is that much higher growth-rates can be seen to exist so that the results are in much better agreement with experiments. Sen showed numerical results based on the non-classical solution to illustrate this point. Sen also mentioned that there was no contradiction with the uniqueness of solutions, because different eigenvalues were attributable to different mode-shapes. It so happens that the non-classical solution yields an eigenvalue with a higher growth rate.

J. S. B. Gajjar of Manchester University, UK, spoke on 'The stability of 3D boundary layer flows'. The flow configuration chosen was flow over a rotating disc. The problem was investigated using a combination of asymptotic and numerical methods for studying the linear and nonlinear stability properties of 3D incompressible/compressible boundary layers. Numerical results obtained for linear stability of the rotating disc problem, using a spectral collocation code, were shown to compare well with the earlier results of Balakumar and Malik. The absolute instability results of Lingwood were also verified. In addition, a near-neutral double zero was obtained in the dispersion relationship, indicating that algebraic growth may also be an important mechanism in the breakdown of the boundary layer over a disk.

Gajjar also described the nonlinear stability of cross-flow instability modes in incompressible/compressible boundary layers over a rotating disk, using multiple-scale techniques. The analysis leads to novel integro-partial differential equations for the vortex amplitudes. These equations have a number of interesting properties which may be of relevance to some experimental observations. These include nonlinear saturation, secondary instabilities as well as finite time/distance singularities which may lead to abrupt transition.

On the second day, M. Gaster of Queen Mary and Westfield College, London, spoke on 'Receptivity to free-stream disturbances'. The ultimate goal of transition-related research is to be able to predict the transition of the laminar boundary layer to a turbulent state. One aspect of the problem involves assessing, in a fully quantitative way, the magnitude of instability waves generated by free-stream turbulence. Turbulence in the free stream consists of vorticity fluctuations that convect past the plate (aerofoil) at free-stream velocity. There is, therefore, a mismatch in frequency–wave number spectra between the turbulence and the instability waves; the latter travel roughly at one-third the free-stream speed.

With the scope of the problem as above, Gaster's study was initially concerned with a number of simple boundary value problems. The calculations for perturbations in a steady boundary layer were carried out based on some simplifying assumptions: viz. linearization of the perturbation equations, reduced boundary conditions, together with neglect of boundary layer growth. The flows created by a suction slot and by a shallow bump were determined and compared with the measured flow patterns. The graphs displayed excellent agreement. Studies more recently performed considered 2D and 3D oscillating bumps. These problems were theoretically analysed, and the results compared well with measured data.

Regarding the problem of excitation by free-stream disturbances, the disturbances created by moving boundary value perturbations were calculated by similar methods. Gaster reported that when the boundary perturbation moved with the free-stream velocity, only disturbances related to the continuous spectrum are excited, and no travelling wave modes are generated. The other important point made was as follows. The boundary layer is not strictly a parallel flow, and *boundary layer growth enables the continuous spectrum to couple with the eigensolution*. This can be understood by treating the growing boundary layer as regions of parallel flow joined at a discontinuity. As the disturbance waves pass through the discontinuity, waves of all type are generated. The full receptivity problem would require the solution of the inhomogeneous disturbance equation, and this would need to be done in future.

T. K. Sengupta of the Indian Institute of Technology, Kanpur, investigated the flat-plate boundary layer subjected to very low frequency three-dimensional disturbances. The corresponding modes, called Klebanoff modes, are somewhat different from the classical Tollmien–Schlichting modes. The Klebanoff modes do not admit a viscous critical layer mechanism, because the αR_e-product is small (α is the streamwise spatial wave number and R_e is the flow Reynolds number), as α is very small. With the disturbance streamfunction and the distance normal to the plate given respectively as ϕ and y, it was seen that the ϕ_y distribution does not show a zero crossing. Therefore with the r.m.s. streamwise velocity fluctuation given as $u' = 2|\phi_y|$, the u' distribution does not depict two maxima as in the case of the Tollmien–Schlichting modes. For a fixed R_e and frequency ω_0, a spanwise wave number was chosen as $n\beta_0$, where β_0 is the spanwise cut-off wave number. Following this the eigenvalue(s) α were determined, first roughly by the method of Mack, and later polished by a Newton–Raphson technique. The stability calculations were done by the compound matrix method. Several interesting results were obtained and conclusions drawn thereform. (i) It was found that for these Klebanoff modes, $\alpha_r \sim O(10^{-4})$. (ii) The smallest α_i occurs for the 4th and 5th modes, and *not* for the first (fundamental) mode. (iii) Phase speeds are very small for the higher spanwise modes. (iv) The group velocity in the streamwise direction is about one hundred times larger than that in the spanwise direction. Thus there is streamwise energy transfer. (v) Higher spanwise modes have an eigenfunction compatible with experimental results. (vi) Newer streamwise modes appear as n increases, but these are not dominant. (vii) At very low frequencies (≤ 1 Hz at $R_e = 1196$) the shear layer supports free stream excitation. (viii) The corresponding 2-D disturbances are upstream propagating, and continue to exist at higher frequencies.

V. Kumaran of the Indian Institute of Science, Bangalore, discussed 'Stability of fluid flow in a flexible tube'. The motivation for the work reported was that some past experiments of Krindel and Silberberg indicated that the transition Reynolds number in a flexible tube could be much lower than that in a rigid tube. The geometry chosen for investigation in Kumaran's work is an inner pipe of radius R, surrounded by an elastic wall of radius H, with $H > R$. The relevant parameters in the problem are the Reynolds number $R_e = \rho VR/\eta$, and another property $\Sigma = \rho ER^2/\eta^2$ that depends on properties of the wall material and the fluid, where η is the viscosity and E is the coefficient of elasticity. The equations of motion were set up for the fluid side along with the elasticity equations for displacements in the solid side. Appropriate matching conditions were used at the fluid solid interface. Thereafter, the perturbations were investigated using the usual normal mode analysis. The methods of solution used were a mixture of analytical and numerical methods. Results were presented for the viscous limit ($R \rightarrow 0$), inviscid limit ($R \rightarrow \infty$, $(\rho V^2/E) \sim 1$), and for wall modes for which $(\rho V^2/E) \sim R_e^{-1/3}$.

The main conclusions drawn for the viscous modes were as follows. Instability could occur for $\Gamma = (V\eta/ER)$ exceeding a critical value even for $R_e = 0$. Instability was due to shear work done at the interface. Results could be analytically continued to intermediate Reynolds numbers from the zero Reynolds number limit. Also there is a complex dependence of the critical Reynolds number on the ratio of viscosities of the fluid and the wall. The main conclusions drawn for the inviscid modes are as follows. Parabolic mean flow is stable to axisymmetric disturbances but could be unstable to non-axisymmetric disturbances, though both kinds could be unstable in the developing region of flow. Also, transport of energy due to shear work at interface is balanced by opposite transfer due to convection. And, dissipation in the wall has a stabilizing effect. The main conclusions drawn for the wall mode are as follows. Introducing the parameter $\Lambda = (E/\rho V^2)$, it is seen that the least stable solution does not converge to any of the rigid tube solutions, but has a frequency that diverges proportional to $\Lambda^{1/2}$ for $\Lambda >> 1$. By numerical analysis it is found that this mode becomes unstable when $\Lambda < \Lambda_c$ at fixed R_e, or when $R_e > R_{ec}$ at fixed E (subscript c depicting critical values). And, stability characteristics are similar to that of viscous modes for $R_e >> 1$.

J. H. Arakeri presented his work with D. Das on 'Transition of unsteady velocity profiles with reverse flow'. This is very interesting because it can be looked upon as either stability theory invoked to explain experiments, or as an experiment performed to verify some precepts of stability theory. The experimental set up (for pipe flow) consists of two straight and long lengths of a pipe connected at the ends in a loop. A piston motion in one of the pipes induces quasi time-dependent flow in the other pipe, which also contains the test section for visualization. The piston undergoes what is called 'trapezoidal' motion: viz. rapid acceleration from rest, followed respectively by a long period of constant velocity, rapid deceleration to rest, and a long period of rest. The velocity–time curve of the piston looks like a trapezium. During the long rest phase of the piston, i.e. at the last phase of the cycle, the flow through the second pipe (which contains the test-section) has reverse flow at the walls, and the velocity profile is inflectional. As time elapses, the effect of viscosity is to reduce the difference between the maximum and minimum velocity (since piston motion has already stopped) till the fluid comes to rest. The centre of attention is the period during which the velocity profile is inflectional. Interesting observations were made, and conclusions drawn, both based on visualization studies and by stability analysis. A video-film was also shown on the visualization experiments.

Visualization studies showed that the flow in the inflectional velocity profile becomes unstable with possibly a helical vortex forming. The wavelength of the instability is $\simeq 3.1\bar{\delta}$ where $\bar{\delta}$ is the average boundary layer thickness, the average being taken over the time the flow is unstable. The time of formation of the vortices scales with the average convective time scale and is $\cong 37\bar{\delta}/\Delta u$, where $\Delta u = (u_{max} - u_{min})$ and u_{max}, u_{min} and δ are respectively the maximum velocity, minimum velocity and boundary layer thickness at each instant of time.

Quasi-steady linear stability analysis bring out two important points. First, that the stability characteristics of velocity profiles, with reverse flow near the wall, collapse when scaled with the above variables. Second, that the wave number corresponding to maximum growth does not change much during the instability phase even though the velocity profile changes substantially. Further, the instability is essentially inviscid and growth rates scale with convective instabilities. Even at large Reynolds numbers the viscous effects are unimportant because the velocity profiles change significantly during the period of instability. Further, the time to instability is $t = 28\delta/\Delta u$, and the time to vortex formation is $t = 37\delta/\Delta u$. It is also seen in the study that, despite instability occurring along with the associated vortex formation, transition to turbulence does not occur unless the Reynolds number based on boundary layer thickness exceeds some critical value. And, when transition does occur, it occurs very rapidly. An estimate shows that with the characteristic time to instability given as $t = 28\delta/\Delta u$, and with $\alpha = 2\pi/(3.1\delta)$ and $c_i = 0.15\Delta u$, the total amplification for wave formation is $e^{\alpha c_i t} = e^{8.5}$. Also, with characteristic time for vortex formation as $t = 37\delta/\Delta u$, the total amplification for vortex formation is $e^{11.2}$. These figures for amplification compare well with the e^9 growth typical of transition to turbulence. Thus many aspects of transition in oscillating pipe flow seem amenable to explanation based on visualization and stability studies. T. K. Vashist contributed to the development of the stability code.

D. Venkateswarlu of Vignana Jyothi Institute of Engineering and Technology, Hyderabad, spoke on his work with P. K. Sen on 'The stability of pipe-Poiseuille flow'. This is one of the few papers in the conference where nonlinear stability was discussed. The formulation of the problem was based on the Stuart–Watson methodology using the equilibrium amplitude assumption of Reynolds and Potter. The disturbance streamfunction is decomposed into a fundamental ϕ, and harmonics ϕ_n with $n \geq 2$. Further, each level of harmonic is in turn expanded in a series, in terms of powers of the amplitude A of the fundamental. The amplitude A in turn obeys the Landau equation, viz.

$$\mathrm{d}A/\mathrm{d}t = \alpha c_i A + \alpha A \textstyle\sum_{n=1}^{\infty} k_n A^{2n}.$$

In the equilibrium amplitude formulation employed, $\mathrm{d}A/\mathrm{d}t$ is *ab initio* set equal to zero, in anticipation of equilibrium states, and the Landau constants k_n determined. Following this the equilibrium amplitudes A_e are determined. Since pipe flow exhibits no neutral curve to linear disturbances, the aim of the work was to see whether destabilization of the flow could take place in the presence of finite amplitude disturbances. The results for A_e were obtained by accelerated convergence methods using the method of Pade approximants. Finally, a curve for A_e versus the Reynolds number R_e depicted significantly that A_e decreased with R_e and was as low as around $A_e = 0.002$ at $R_e = 6000$. Thus it was concluded that finite amplitude disturbances could destabilize pipe flow. One notable feature of the work was the Noumerov transform molecule developed for $O(h^6)$ accuracy up to the fourth derivative in ϕ, and with a seven-point finite difference scheme.

T. K. Vashist of Centre for Airborne Systems Bangalore, spoke on 'Stability of compressible boundary layer flow'. He described the status of the work done so far by himself. The set of disturbance equations based on the linearized Navier–Stokes equations, continuity equation, energy equation, and the equation of state, results in an eighth order system in the disturbance variables u', v', ω', T', p', respectively depicting the three velocity components, and temperature and pressure. This is reduced to four ordinary, second-order, coupled differential equations by normal mode analysis. The boundary conditions at the edge of the boundary layer are the exponential decay conditions. At the wall, the velocities u', v', $\omega' = 0$. Also the temperature T', if expressed as overheat with respect to the wall, satisfies the condition $T' = 0$. However, the pressure term p', appearing only up to the first derivative, can satisfy only one boundary condition, and $p' \neq 0$ at the wall. The pressure term either needs a special condition to be derived at the wall, or it has to be eliminated altogether by cross differentiation. In addition, the mean flow and temperature fields need to be determined or prescribed. Vashist described a method for obtaining the mean flow for the two-dimensional case. He also described his numerical formulation for the eigenvalue problem. After the usual normal mode analysis in the form

$$\{u,' v', \omega', T', p'\} = \{f(y), g(y), h(y), \theta(y), P(y)\} \exp \{i(\alpha x + \beta z - \omega t)\},$$

the problem was first converted into finite difference form using a Noumerov transform developed for the purpose, such that the errors were $O(h^6)$ in all the derivatives (up to the second order) with only a five-point scheme. After concatenation of the matrix the non-zero terms were along the leading diagonal. Thereafter, the eigenvalues were sought to be determined first by the Thomas method, i.e. based on Gaussian elimination; and second, by the Q–Z algorithm. It is at this point that success is still awaited because the eigenvalues obtained so far seem not to tally with those existing in published literature. Further work is going on to make the programmes operational.

N. Rudraiah, of UGC-DSA Centre in Fluid Mechanics, Bangalore University, spoke on 'Linear and nonlinear Rayleigh–Taylor instability'. Rayleigh–Taylor instability occurs when a heavy fluid is supported by a lighter fluid in the following configurations:

(i) When there is a thin fluid layer supported by a rigid-plate below, and on top there is a densely packed porous layer with a heavy fluid.

(ii) When there is a thin film consisting of a fluid saturated porous layer, supported by a rigid plate below, and with a heavy fluid above.

Apparently these problems have not been investigated in spite of their importance in materials science, inertia-controlled fusion, astrophysics, geophysics, and biomechanics. The crux of the problem is to specify a proper boundary condition at the interface between the fluid and the porous medium. When the thickness of the porous layer, bounding the thin fluid above, is large, the slip boundary conditions that could be used are either the Beavers and Joseph condition or the Saffman condition. These boundary conditions are independent of the thickness of the layer, and hence valid only when the thickness of the porous layer is comparatively very large, as is the case in geophysical and some industrial problems. On the other hand, in many biomechanics problems the thickness of the fluid layer plays an important role; and, this led to a new boundary condition to be proposed by Rudraiah. This boundary condition is more suitable because it involves the film thickness. Using all the three conditions stated above, Rudraiah obtained the dispersion curve, and arrived at the following conclusions:

(i) The shape of the dispersion curve is mainly controlled by the surface tension and buoyancy forces, and the porous parameter and the thickness of the layer.

(ii) With suitable values of porous and slip parameters, both stable and unstable interfaces are found to exist.

A. Prabhu of the Indian Institute of Science, Bangalore, spoke on his work with J. Dey, R. Narasimha, M. Jahanmiri, S. V. S. Phanikumar and O. N. Ramesh, on 'Three dimensional spots'. This was a report on a series of experiments carried out in a distorted duct to study the effect of streamline curvature (transverse), followed by divergence with straight streamlines, on the structure of a turbulent spot. The experimental set up comprised a uniform duct, followed by a distorted duct that became uniformly narrower in the vertical direction and uniformly wider in the transverse direction. This ensured that there was no pressure gradient in the distorted duct since the average sectional velocity was maintained constant. Nevertheless, distortion of the duct caused the streamlines first to curve, and then to diverge (as straight streamlines), in the spanwise direction. The spot source, consisting of a pulse of air through a static hole on the test flat plate, was located in the uniform section upstream of the distortion. This spot spread and propagated downstream, and generally moved along the direction of the curved streamlines, followed by the diverging straight streamlines. Typical measurements were carried out at 0.5 mm above the bottom flat plate. It was found that the distortion produces substantial asymmetry in the spot. The angles at which the spot cuts across the local streamlines are altered dramatically (in contradiction of a hypothesis commonly made in transition zone modelling), and the Tollmien–Schlichting waves that accompany the wing-tips of the spot are much stronger on the outside of the bend than on the inside. However, there is no great effect on the inner structure of the spot and the eddies therein, or on such propagation characteristics as overall spread rate and the celerities of the leading and trailing edges. Both lateral streamline curvature and non-homogeneity of the laminar boundary layer into which the spot propagates, appear to be strong factors responsible for the observed asymmetry.

J. Dey of the Indian Institute of Science, Bangalore, presented his work with R. Narasimha on 'Momentum balance in the linear-combination integral-model for the transition zone'. The linear-combination integral method of Dhawan and Narasimha for transition zone modelling is one among various models now available. The momentum balance aspect of this integral model was taken up for discussion, in the presentation. In the Dhawan–Narasimha model the velocity u and the skin-friction coefficient C_f are expressed in composite form in terms of the laminar ('L'), turbulent ('T'), and composite ('lc') parts, and in terms of the intermittency γ. The expressions are

$$u = (1-\gamma)u_L + \gamma u_T; \text{ and,}$$
$$C_{flc} = (1-\gamma)C_{fL} + \gamma C_{fT},$$
$$\gamma = 1 - \exp(-0.41\xi^2);\ \xi = (x - x_t)/\lambda$$
$$\lambda = x_{\gamma=0.75} - x_{\gamma=0.25},$$

where x is the streamwise co-ordinate. It was pointed out by Green that the method could lead to a momentum imbalance for constant pressure flow. To evaluate the error, the momentum thickness is expressed as follows:

$$\theta_{lc} = (1-\gamma)\theta_L + \gamma\theta_T + \gamma(1-\gamma)\int (u_L - u_T)^2 dy,$$

where θ is the momentum thickness. Thereafter, noting that

$$d\theta_L/dx = 0.5C_{fL} \text{ and } d\theta_T/dx = 0.5C_{fT},$$

one obtains

$$d\theta_{lc}/dx - 0.5C_{flc} = I_1 + dI_2/dx,$$

where

$$I_1 = (\theta_T - \theta_L)d\gamma/dx, \text{ and}$$
$$I_2 = \gamma(1-\gamma)\int (u_L - u_T)^2 dy.$$

Thus the error is given as $I_1 + dI_2/dx$. The present results were verified with respect to past experimental results on transitional boundary layers. The conclusion was that the momentum imbalance was amounting to about 2% in drag in the transition zone.

The next paper was by O. N. Ramesh, of the Indian Institute of Science, Bangalore, who presented his work with J. Dey and A. Prabhu on 'Transition zone in a constant pressure laterally diverging flow'. Experiments were conducted in a distorted duct having lateral divergence of streamlines under constant pressure (set-up already described in presentation by Prabhu), in order to study the effect of lateral strain rate on natural transition. Measurements showed that the normalized intermittency distribution follows the universal intermittency distribution of Narasimha. This is used to predict the transitional velocity profiles using a linear combination model which combines laminar and turbulent velocity profiles with intermittency as the weighting factor. With the symbols same as in Dey's presentation, the composite expression for the velocity profile is $u = (1 - \gamma)u_L + \gamma u_T$, where u_L is given by the Blasius solution, and u_T is given by the log-law. Predictions made thus agreed very well with experimental measurements.

M. Nandanan, of Aeronautical Development Authority, Bangalore, spoke on 'Role of transition prediction in advanced transport aircraft design'. The paper was very significant in that it was a status report on where the Indian aeronautical industry stood, in relation to design and development of advanced transport aircraft. The available design tools were discussed, and so were the areas that needed urgent indigenous development, transition prediction being one of them. Nandanan pointed out that 65% of the total drag in a typical transport aircraft is due to friction; therefore, any future design should aim at reducing this. This is only possible if the designer can succeed in keeping the flow over the wing laminar to as large an extent as possible. Nandanan then went on to describe the design methodology of wing aerofoil sections, for keeping the flow laminar to as large an extent as possible. A typical laminar flow airfoil designed by Aeronautical Development Authority was tested in the 1 foot NAL transonic wind tunnel to study whether the airfoil sustains laminar flow. The test data and the computational results showed good agreement, and the lift/drag (L/D) ratio was found to improve by about 41% when the transition strip was removed for the free transition case. The NAL wind tunnel does not have the facility of measuring transition location. Therefore, the transition predictor of Govindarajan and Narasimha was used to estimate the location of transition. This predicted that transition was likely to occur at 34% of chord, both on upper as well as lower surfaces of the airfoil.

Whilst the above was no doubt an impressive first effort, Nandanan also pointed out the immediate needs for further design work in the aeronautical industry. In so far as 2D design tools are concerned, the Indian aeronautical industry has capabilities for airfoil design and analysis. It also has capability of transition prediction. However transition predictors based on stability calculations, for the compressible flow case, are still not available. For the 3D case, codes are available for full potential flow calculations, and for (integral methods based) boundary layer analysis. The shortfalls are: first, it is necessary to be able to calculate the details of the (three-dimensional compressible) flow within the boundary layer; second, to be able to do 2D and 3D stability calculations for the compressible flow case; and third, to be able to make predictions for the line of transition, along the wingspan, based on the stability calculations. Nandanan also mentioned that cross-flow instability could be playing an important role in the transition of the flow past the designed wingspan; and, study of this kind of instability also needed to be brought within the purview of transition predictors that need to be developed in future.

R. Narasimha, of the Indian Institute of Science, Bangalore, spoke on 'Sub-transitions in the transition zone'. He presented experimental evidence for the view that the transition zone may, under certain conditions, be considered to contain what he called sub-transitions. Such sub-transitions could occur in a variety of situations. For example, a boundary layer subjected to pressure gradient over part of the transition zone could show a kink in the intermittency distribution – or more precisely in a function of the intermittency that is a proxy for the spot width. Favourable pressure gradients in the beginning of the transition zone were more effective in producing such sub-transitions than those that occur later, presumably because the same gradient in a flow that is closer to the fully turbulent state can be expected to have a weaker effect than on a nearly laminar flow. Narasimha showed detailed measurements in some flows where the location of the sub-transition as inferred from intermittency coincided with abrupt changes in local boundary layer parameters. Inference of sub-transition in some flows reported by Blair, made on the basis of an analysis of indirect experimental evidence, was later confirmed by direct measurements of intermittency. Narasimha attributed such sub-transitions to rapid changes in spot parameters, which could occur in a flow if it went from sub-critical to supper-critical and vice versa depending on the pressure gradient it is subjected to, especially in the early part of the transition zone. Changes that occur on three-dimensional surfaces could also be instances of sub-transition. For example, on an axisymmetric body, a spot would first propagate as on a flat plate, but would eventually wrap around the body and propagate as a sleeve, as pointed out by Rao. This leads to a marked and relatively abrupt change in the nature of the intermittency distribution, which can now be predicted by a consistent theory, and could also be considered a kind of sub-transition. Narasimha emphasized that as interest grows in the transition zone in more complex flows, greater care would have to be given to the occurrence of such sub-transitions.

P. K. Sen spoke on his work with Srinivas V. Veeravalli on 'Stability of an organized disturbance in a turbulent boundary layer'. Here, the use of hydrodynamic stability theory in understanding the dynamics of wall bounded turbulent flows was discussed. This approach has remained somewhat dormant since the works of Reynolds and Tiederman, and Reynolds and Hussain. Reynolds and Hussain derived an extended Orr–Sommerfeld equation to describe the evolution of an organized disturbance in turbulent flow, based on what they called the Newtonian eddy model. This equation was independently derived in the present work by an alternative more compact route, using an isotropic eddy viscosity model. Although one obtains near neutral modes with this equation, there are no unstable modes. A further extension was made in the present work to incorporate a more general anisotropic eddy viscosity model. The final disturbance equation thus obtained does yield an unstable wall mode, and, the results seem to mimic some key features of fully developed wall turbulence. Numerical results were reported for the flat-plate turbulent boundary layer. The eigenfunction, the root mean square distributions of the organized disturbance velocities $\tilde{u}$ and $\tilde{v}$, and, the $\overline{\tilde{u}\tilde{v}}$ profile, are similar in form to those obtained for the case of the laminar boundary layer. So also is the value of the phase speed which is $c_r \simeq 0.3$. Thus both phenomena appear to be governed by the high shear region near the wall. The production peak, corresponding to the organized disturbance problem, occurs at $y^+ = 12.5$ which agrees well with the location reported in past experiments on the turbulent boundary layer. The band of unstable wave numbers also matches well with the turbulent u' power spectra measured (as part of the present work) in the buffer and log regions of a flat-plate turbulent boundary layer.

I. S. Shivakumara, of UGC-DSA Centre in Fluid Mechanics, Bangalore University, spoke on his work with N. Rudraiah on 'Effect of throughflow on Rayleigh–Benard convection'. Onset of convection in a horizontal fluid layer with throughflow in the vertical direction was investigated for different types of hydrodynamic boundary conditions (i.e. rigid–rigid, free–free and rigid–free boundaries). The critical Rayleigh numbers were obtained numerically using the Galerkin technique. It was found that throughflow, irrespective of its direction, makes the system more stable when the boundaries are of the symmetric type. However, when the boundaries are of different types, a small amount of throughflow in one particular direction destabilizes the system depending on the value of the Prandtl number P_r. It was further noted that the destabilization is small for $P_r \approx 1$, and increase in the same causes decrease in the critical Rayleigh number. Also, it was found that increase in magnitude of throughflow increases the critical wave number.

M. Gaster gave the last talk on 'Prospects for active control'. Here, some possible schemes for wave cancellation based on active control were discussed and reviewed. A single monochromatic wave, introduced in a controlled manner, could be cancelled further downstream by introducing another disturbance source that is made to be in opposite phase by active control. However, although this is an interesting laboratory experiment to perform, this does not automatically guarantee transition control; because, in a real life situation the intrinsic disturbances leading to transition expectedly have a much more complex composition as compared to a single monochromatic disturbance wave as in the case of the typical laboratory experiment. Active cancellation of an arbitrary disturbance is still a far cry. Nevertheless, Gaster showed some analytical and experimental results which are very promising. These pertain to generation of a wave packet and active cancellation of the central part of the wave packet by using a piston plunger arrangement downstream. The approach seemed very promising and is a major contribution towards achieving the goal of active control.

After Gaster's talk, R. Narasimha gave an overall summary of the entire conference.

P. K. Sen, Department of Applied Mechanics, Indian Institute of Technology, New Delhi 110 016, India.