Boundary layer transition in turbomachines*

Almost four years after the Workshop on End-Stage Transition (*Curr. Sci.*, 1994, **67,** 6–9; Proceedings of the Workshop) now seen as Minnowbrook I, nearly 50 participants gathered again at the same lovely site on the initiative of the same organizers (John Lagraffe of Syracuse, Paul Gostelow of Leicester and Terry Jones of Oxford). As Lagraffe reminded his audience in his opening remarks, the first workshop had sought to bring together two different communities involved in transition research: the *Journal of Fluid Mechanics* and American Society of Mechanical Engineers types, or high and low church, as Paul Gostelow had described them. The present workshop had a sharper Focus on turbomachinery flows.

Roddam Narasimha (JNC/IISc, Bangalore) started the proceedings by reviewing what had transpired at and after Minnowbrook I. The distinguishing features of transition in turbomachinery flows are that they are unsteady on time scales longer than typical eddy turnover times, occur in harsh and highly disturbed environments at awkward Reynolds numbers, and are generally three-dimensional (even in the mean). As a consequence, the flow is a veritable fluid-dynamical 'zoo', characterized by separation, reattachment, transition, relaminarization, retransition, etc., all often occurring in the *same* flow. Greg Walker (Tasmania), in his keynote talk the next day, noted how 'interesting' the problem was, and that this may be a version of the well-known Chinese curse about living in interesting times for turbo-machinery fluid dynamicists. Nevertheless, as Narasiinha noted, there had been inuch progress on many fronts, but it was remarkable that ideas related to dynamical chaos, which at first appear so closely connected with transition to turbulent flow, had made so little impact on the subject they were going to discuss at the meeting: the reduction in the number of degrees of freedom that such ideas have till now provided is clearly not sufficiently significant to make a practical difference.

Minnowbrook I had been dominated by discussions on spots and modelling. Minnowbrook II saw much attention devoted to the characteristics of the calmed zone trailing a spot and the possibilities of its exploitation, and the understanding and management of separation bubbles and unsteady transition.

But how important *is* transition research for the turbomachinery industry? Walker cited GE compressor tests (made by Halstead) showing transition extending over G0% of the blade chord, and estimates of potential improvement in efficiency by several percentage points; considering how widely turbomachines are used in energy conversion and propulsion systems, significant economic and environmental benefits are possible. David Wisler (GE Aircraft Engines, Cincinnati) pointed out that the 'lack of ability to predict the location of boundary layer transition for components in gas turbine engines is impeding our ability to gain maximum benefit from our design effort'. If a complete computational fluid dynamics (CFD) design tool incorporating transition were to be available, he foresaw airfoil designs with higher blade loading that would reduce part count and improve efficiency. He estimated that a 1% improvement in the efficiency of a low pressure turbine would result in a saving of $52,000 per year on a typical airliner, but he was willing to accept even 1/2% provided it was reliable. Improved transition technology was thus very relevant. However, Wisler thought it was unlikely to have a major impact on design: the gas turbine industry is now maturing, and is generally driven by cost and 'error-proofing' the design rather than higher performance *per se*.

Apart from the gains that may be achieved if a reliable CFD design tool were to be available, where should one look to improve efficiencies now? The answer, as summarized by Greg Walker and widely endorsed during the meeting, appears to lie in the exploitation of the calmed region trailing a spot, understanding the time-dependent forcing of transition in a turbine row because of wakes from upstream rotor stages, and the management of separation bubbles.

Narasimha considered three-dimensionality important, and David Ashpis (NASA Lewis) listed 3D effects ('virtually unknown' in his words) as one of the barriers to progress. Several participants highlighted transition, separation and wake–boundary layer interaction as the tnajor problems in turboinachinery boundary layers. Ashpis noted a 2% drop in efficiency From take-off to cruise (as the Reynolds number drops typically from about 200,000 to 80,000), and minimizing this loss was one of the objectives of the NASA Low Pressure Turbine (LPT) Flow Physics Program (which involves 6 industries, 6 universities and 3 government laboratories).

The calmed region

The possibility of exploiting the calmed region had been foreseen already in the pioneering work of Schubauer and Klebanoff, who wrote in 1955 [as Howard Hodson (Cambridge) reminded us] that 'turbulence injected at the proper time intervals can in principle alleviate the severity of the turbulence "disease"'. As of today there is no clear demonstration of the efficacy of this 'vaccination' principle – as we may call it – but there are now indications of how it might be done.

Terry Jones and John Lagraffe described work showing that the behaviour of the calmed region could be seen as the resumed growth of a disturbed laminar layer; the rate at which the calmed region trailing a spot grows is defined by the time for a new boundary layer to grow from the point where the spot was born. This view leads to a good prediction of the duration of calming, and a collapse of measured heat flux data as a function of time normalized by the duration so estimated.

Paul Gostelow pointed out that as **the** flow in the calmed region is more stable than the boundary layer it replaces, it delays separation and suppresses instability. In experiments on a flat plate subjected to strong adverse pressure gradients, Gostelow finds that the calm region behind a triggered spot is extensive. Its interaction with the natural

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boundary layer is complex, and depends on whether the boundary layer is laminar or turbulent. He introduces a new relaxation parameter to quantify and describe the calmed region, and uses the data obtained to validate his model for transition.

Hodson showed some experimental data indicating that a *higher* frequency of inducing transition spots could reduce the loss coefficient and trailing-edge momentum thickness. Ari Seifert (Tel Aviv) reported on experiments showing that a train of spots generated some 200 momentum thicknesses *upstream* of the transition onset location can lengthen the transition zone and so significantly *reduce* the intermittency downstream in the transition zone; whether this would compensate for the *increase* in intermittency upstream and so actually reduce drag is not yet clear.

Unsteady transition

The time-dependent forcing of transition already referred to attracted considerable attention at the meeting. Pavel Jonas (Prague) reported interesting measurements on the transilion zone at different turbulence levels with superposed periodic oscillations of free-stream velocity (obtained by rotating a flap at the trailing edge of his test-surface). When the frequency of oscillation is low, the final part of the transition zone is considerably longer, and the (average) skin friction shows non-monotonic variations in space; but if the frequency is high the transition is rapid as in a turbulent-free stream. The changes appear to correlate with an unsteady Reynolds number directly proportional to the velocity amplitude and inversely to the frequency, with a critical value that determines whether the frequency is 'high' or 'low'. Jonas also reported on the effect of turbulence length scale, which he could vary over a range of 1:15 in his facility without altering the turbulence intensity; he found a delay in the later stages of transition when the scales were small. Hodson reported experiments using surface hot films from unsteady cascade as well as full scale rig testing in an altitude test facility. David Halstead (GE Aircraft Engines, Cincinnati) showed detailed measurements of flow field unsteadiness in multi-stage compressors and turbines. These experiments provide not only the intensity and the spectrum, but also measurements of the length scales in a low pressure turbine. The complexity of the unsteady flow field between blade rows was shown to increase markedly through the turbine. At the inlet of the second stage nozzle, the unsteadiness correlates with the clocking position of the upstream nozzle blade row, (Such correlations might 'select' particular blades for failure, as Ashpis noted.) At the exit of the turbine, however, no such correlation could be found, It is clear that the wakes from stator and rotor blades upstream get chopped up, and that at some stage in the machine identification of the origin of various chunks of turbulence will become difficult, but it is not clear how deep into the machine one has to go before this happens. At the exit of the turbine there is no discernible 'free-streain' region, suggesting that experiments with moving wake generators upstream of a cascade or single stage will not simulate many features of the flow field in a multi-stage machine.

Om Sharma (Pratt and Whitney, E. Hartford) showed experimental data from an engine and a model rig to highlight current lack of understanding of the actual operating environment in the gas turbine engine. Analytical results showed the limitations of transitionlturbulence models now in use in the low Reynolds number environment of low pressure turbines; this problem is important because of the loss in efficiency during cruise at altitude, where Reynolds numbers tend to be low relative to take-off conditions.

Separation bubbles

Separation bubbles are another characteristic Feature of many turboinachine blade flows. Ting Wang (Clemson) sketched three hypothetical modes of transition involving bubbles: (i) the short bubble at low Reynolds numbers (Re) and mild adverse pressure gradients, (ii) the long bubble – also at low Re but in strong adverse pressure gradients (in both cases the separating flow is laminar), and (iii) the transitional bubble. In the short laminar bubble, transition onset occurs at maximum displacement point, and maximum turbulence intensity *(u')* at (turbulent) reattachment. In the long bubble, there is a short, early transition region leading to the first reattachment type behaviour, but the strong pressure gradient does not admit attached flow; a long and late transition occurs in the bubble before actual reattachment. The transitional bubble occurs at high Re and mild adverse pressure gradients. Here transition begins before separation and tends to house a long initial region (because of the constant pressure plateau induced by the bubble), and is followed by a short completion phase. Maximum u' occurs near the maximum displacement point. Ting Wang presented correlations for the Re values associated with bubble events as a function of an acceleration parameter for all three modes.

Nick Cumpsty (Cambridge) presented measurements showing how free stream turbulence and incidence have a large effect on the nature of the separation bubble. At low incidence no evidence of spot transition could be seen, but at higher incidence and low free stream turbulence, spots were clearly visible in the bubble shear layer.

Fred Simon expressed surprise that even in separation bubbles the intermittency followed Narasimha's universal distribution, although the Emmons spot was presumably specific to wall-bounded flows. Narasimha explained that the universal distribution depended on three postulates: Poisson birth, linear propagation and concentrated breakdown; and if these were satisfied the universal distribution follows, whether or not the Emmons spot is involved, Thus, he had found that the temporal development of phase transition in metals followed the same or related distributions.

Stability

Eli Reshotko (Case Western) surveyed the role that transient growth (first invoked by Landahl in 1980 to explain the lift-up mechanism in boundary layers) can play, especially in roughness-induced transition (where there may be no evidence of TS waves), and presented a new picture of possible paths to turbulence in wall layers. In the canonical TS route such transient growth is benign and insignificant. Other routes are that transient growth provides higher input to eigen-mode growth or directly excites secondary instabilities. Finally, transient growth can feed into the bypass mechanism. With very large forcing possessing a crazy spectrum, Reshotko thought bypass mechanisms can be directly excited without transient or eigen-mode growth. Interestingly he found evidence of transient growth in pipe experiments conducted at JPL in 1961 !

Herbert reported that the PSE codes that work so well for external flows are less successful for turbomachinery blades, Among various possible causes, he found there could be a serious problem even in the specification of the geometry of the blade (usually co-ordinates are given at too many points but to too Sew decimals). Further, computed pressure distributions do not agree with measurement (blockage corrections? gradients in outer inviscid flow? non-zero wall-normal pressure gradients?); these problems need to be sorted out first. At any rate, his codes have now seen various improvements like extension to swept-wing flows and inclusion of Klebanoff modes.

Narasimha briefly described work done with Rama Govindarajan (NAL, Bangalore) on a new formulation of boundary layer stability. This work leads to a hierarchy of three equations, most easily formulated for the Falkner–Skan similarity solutions. The highest member of the hierarchy is compatible with Herbert's PSE, but at this order consistency in approximation demands that account be taken of higher-order boundary layer theory, which presents difficulties and is therefore generally (but unjustifiably) ignored, The next member of the hierarchy is a lower order parabolic (LOP) p.d.e. that is simpler than the Herbert PSE; this is the *highest* order rational theory that can justifiably neglect higher order boundary layer effects. At sufficiently large Reynolds numbers, this LOP theory reduces to an o.d.e that is like Orr–Sornmerfeld but not identical: two viscous 0–S terms are absent but an additional term representing the transport of vorticity by the mean wall-normal velocity is present. All three members of the hierarchy apply to non-parallel flow. Results show significant differences from Orr–Sommerfeld only in strong adverse pressure gradients; in free shear flows the boundary of absolute instability can be substantially different, and this may be important for understanding separation bubbles.

Frank Smith (London) reported theoretical studies on near-wake transition, inspired by the need to understand rotary-blade/wake interactions. The near-wake may exhibit *two* length scales, bechuse of the presence of a thin inner sublayer within a thicker boundary layer. He noted that a favourable pressure gradient may *destabilize* a near wake because of the negative profile curvature it induces. Smith highlighted various issues in which the stability characteristics of the wake – absolute or convective, linear or nonlinear – may be relevant to transition problems on blades.

Modelling

Models for the transition zone are now proliferating rapidly, and are being generalized to the unsteady situations prevailing in turbomachinery. Narasimha described briefly an improvement made by Dey (IISc, Bangalore) to linear-combination models, so that they can take account of the calming period and ensure better momentum conservation. Fred Simon (NASA Lewis) presented models that utilize the dependence of spot characteristics on pressure gradient and Mach number for predictions of heat transfer; he uses the intermittency model of Solomon, Walker and Gostelow and correlations for the non-dimensional spot formation rate of Narasimha. He finds that relative changes can be estimated well independently of the model, but it is important to incorporate Mach number effects. His model gives good agreement with the data of Arts *et al.*

Johnson (Liverpool) uses a distributed breakdown model, postulating that spots are induced whenever the instantaneous velocity drops 50% below the mean – inducing transient local separation (an idea that I must point out goes back to G.I. Taylor). By making suitable assumptions on the proportion of minima that induce spots, Johnson provides a good fit to the intermittency near onset. With correlations for the spot formation rate parameter of Narasimha, he is able to get good agreement with the data of Abu-Ghannam and Shaw and Gostelow.

Fraser (Dundee) has implemented a transition model within the PHOENICS package. This is a linear-combination integral model, with correlations for the start of transition. The integral model is a set of coupled ordinary differential equations, generated from a $K\varepsilon$ type equation making certain simplifying assumptions. Comparisons were shown for several ERCOFTAC test cases, but I noted that the peak skin friction coefficient is always under-predicted.

Lakshminarayana (Penn State) described recent work on a low Reynolds number $K\varepsilon$ model; he found the Fan–Lakshminarayana–Barnett version gave the best results. The model is able to predict the occurrence of the major regions associated with wake-induced transition, including the calmed zone and the transition strip.

Steelant (Gent) has pursued the idea of modelling by-pass transition through conditionally averaged flow equations, each carrying interaction terms that depend on the conditionally averaged velocities as well as the intermittency γ, which is determined either algebraically (after Dhawan and Narasimha) or through a separate transport equation. Reasonable agreement was reported with the ERCOFTAC flow T3C5.

Guohua Xiong (Kentucky) also uses conditioned $K\varepsilon$ equations with a transport equation for γ, to predict transitional flows in low-pressure turbines, When an allowance is made for the normal variation of γ through the Klebanoff distribution, Xiong finds good agreement with the ERCOFTAC turbine series of test cases.

Daniel Dorney (GMI Institute, Flint MI), using Baldwin-Lomax, $K\varepsilon$ and $q\omega$ models, reported on both cascade and stage simulations of unsteady transition. The first two models give similar results on cascades. At a Reynolds number of 80,000, a transition limit cycle appeared in the solutions. They remind me of Rotta's and Pantalu's observations in a pipe, but it is not clear if there is a connection.

Mark Savill (Cambridge, not present at the meeting) circulated a useful report about the coordinated European programme being promoted by the ERCOFTAC Transition Modelling Group. The programme now includes 15 groups outside Europe as well, and is becoming a major international force for assessment of transition models – often carried out 'blind', i.e. without access to test data, or even in advance of its acquisition. **A** total of 15 test cases have so far been released to participants. Savill's report for Minnowbrook contains a detailed description of model performance in various cases.

DNS/LES

In his opening remarks, Narasimha made what he called a 'modest proposal', which was to do Direct Numerical Simulation (DNS) (and possibly also Large Eddy Simulation (LES)) on a realistic blade, but in the manner advocated in Minnowbrook I (i.e. in 'mission mode'). He suggested beginning with the 2D case, with progressive 'complexification' in the geometry (to 3D), specification of the disturbance environment (wake-passing), inclusion of compressibility effects, cooling, etc. The current state of the art was discussed in several presentations. Manmohan Rai (NASA Ames) simulates the spatially-growing boundary layer on a heated flat plate in the presence of relatively high free-stream turbulence. The simulation involves 24×10^6 grid points. The basic physics of transition is captured, but computed onset is slightly downstream of observed onset in the experiments of Sohn *et al.* (which Rai simulates). It is not clear why the fully turbulent boundary layer far downstream appears to originate at the leading edge, and has a profile without a wake region. Interestingly, Rai found no evidence of negative eddy thermal flux, of the kind that some experiments have (controversially) reported.

Neil Sandham (Queen Mary and Westfild) has now carried out simulations of separation bubbles showing laminar separation, transition and turbulent reattachment, on a 128-processor Cray T3D (achieving 90% parallelization efficiency and needing 20,000 processor-element hours at around 3 gigaflops). Sandham considered that fully-resolved DNS of separation bubbles, and single and multiple spot calculations, are now feasible.

D. J. Doorly (Imperial College) uses the vortex particle-in-cell method to study wall-layer dynamics and vortex–surface interactions. In a model problem, a 2D vortex suddenly imposed on a wall is shown to lead to eruption of boundary-layer vorticity into the free stream.

Miscellaneous

William Saric (Arizona State, Tempe) summarized the detailed experiments being carried out in the ASU Unsteady Wind Tunnel to understand receptivity to free stream disturbances, in particular the large-amplitude noise characteristic of turbine engines; the problem cannot be handled through the usual linear mechanisms. Oblique and broad-band sound waves are used to determine how unstable waves are initiated. Acoustic disturbances are produced in bursts, and the TS waves detected by a differential phase speed technique. Saric emphasized that theory, DNS and experiment are now in agreement, provided due care is exercised in defining receptivity coefficients.

As Walker pointed out, transition is most important in the LP turbine and compressor, where the blades have relatively high aspect ratio; low aspect ratio blades are largely immersed in the turbulent annulus wall boundary layer. This – and experimental convenience – have led to a large effort in 2D flows. But true 2D flows are rare, and 3D phenomena could be very significant. Narasimha showed results of measurements (made with Jahanmiri and Prabhu) on a spot in a divergent flow with no pressure gradient; it was found that the spot can cut across local streamlines at angles ranging from 3" to 13". On the other hand the spot wedge grows at an included angle of 20°, about the same as in 2D flow. He concluded that divergence only produced a geo*metric* distortion of the coherent structure in the spot (it was no longer symmetrical), but hardly affected its *dynamics.* Narasimha also mentioned the investigation of the 3D transition zone in the same diverging flow carried out by Ramesh, Dey and Prabhu (IISc).

Kohama (Sendai) reported detailed investigations of transition on a swept flat plate with a displacement body. He found two different instabilities apart from the well-known stationary mode: namely a travelling cross-flow instability and a high-frequency secondary instability propagating along the stationary vortex. The turbulent wedge triggered by this instability starts from the middle of the boundary layer on each cross-flow vortex. Koharna also reported on experiments at control using suction.

Tumin (with Eliahou, Han and Wygnanski at Tel Aviv) showed that transition in pipes begins with the distortion of the parabolic velocity profile, and proceeds through stream-wise rolls which amplify and finally break down following spikes as in the K-regime in boundary layers.

Jacques Lewalle (Syracuse) showed how wavelet analysis can be used on hot film series data to characterize and track structures in the flow.

McEligot described a new matched-index-or-refraction (MIR) facility that has been built at the Idaho National Engineering and Environmental Laboratory. The idea is that if fluid and model in a flow facility have the same refractive index, one can use laser Doppler and particle imaging velocimetry techniques to see through objects without disturbing the flow. Problems connected with transition on cascades and flow in cooling holes are proposed to be investigated.

Recommendations

As at Minnowbrook I, working groups were formed to look into selected areas and recommend directions for future research. Terry Jones, who headed the Working Group on the Becalmed Region, pointed out that details at the trailing edge of the spot are not yet understood; e.g., why does it travel at half the free-stream speed? More work needs to be done on practical exploitation, not only to help manage separation, but possibly also aeroelasticity and acoustics.

David Ashpis, whose Working Group considered LPT Physics, called for an 'Engine Flow Environment Measurement Project'. The discussions at Minnowbrook clearly brought out the serious need for such a project. Ashpis further suggested that the project should be international – in execution as well as in the review process. He also highlighted the need for further studies of Mach number and (severe) adverse pressure gradient effects on spots.

Terry Simon reported on behalf of end-users. What industry needs is robust transition/turbulence models for off-design analysis to evaluate design choices and determine optimum designs. ('Robustness' was defined by Wisler as the ability to work over a wide envelope of initial and boundary conditions, Mach and Reynolds numbers, and geometry, without needing special tuning.) Such models have to be integrated into the standard CFD codes. But, interestingly, the Group added that it is necessary to include a presentation of the physics of transition as well, to help engineers in design selection. Finally, the importance of desensitizing the engine to low-Re effects was emphasized.

The fourth Working Group on computations was chaired by Sandham. The Group identified the following DNS tasks as feasible in **3** years on current computer platforms:

- Spots, in a range of pressure gradients, with study of sensitivity of results to method of triggering.
- Separation bubbles on a single blade, at $Re = 50{,}000$, $M = 0.8$. Om Sarma offered cascade B as a candidate, noting that further experiments with well-defined boundary conditions may need to be carried out.

In the 3–10 year time frame, assuming computer power increases 10-fold in **3** years, it might be possible to analyse wake–blade interactions. Doorly felt this would still be expensive. Herbert considered that the biggest problem would be to prescribe the appropriate inflow boundary conditions at the HP turbine.

There was much discussion on how all of this work was to be funded. Ashpis suggested that **NASA,** Department of Energy and the Air Force office of Scientific Research need to formulate a joint strategy For supporting long-term programmes. This is all the more necessary as there are now fewer people in industry working in 'enabling technology groups', so the task has to be accomplished by academia, government and industry working together for visible benefits. Industry was willing to talk, Terry Simon said, if academics were willing to listen!

Conclusion

In his concluding remarks, Narasimha said it is even clearer today than it was in 1993 that turbomachinery boundary layers represent a very interesting and complex flow situation. There are other flows in the same awkward Reynolds number range, such as birds and windmills, but these do not present the complexity that arises from the multiple stages in turbomachinery. The industry is now mature, and costs seem to be driving everything: it is willing to consider even a half per cent improvement in efficiency, but will not easily pay for attaining it themselves.

As far as transition physics is concerned, the increasing interest in separation bubbles is both timely and welcome. With the many interesting studies reported at the meeting, it was his assessment that in the corning few years the bubble problem would be largely sorted out, except of course for all .those more basic questions that might remain in connection with spots and turbulence.

With regard to spots it was gratifying that the studies that he had foreseen in 1985 as essential were now being conducted. The behaviour of spots in pressure gradients, and the effect of Mach number, are slowly getting to be documented. But it is important to realize that we still do not *understand* spots. There is nothing more practical than a good theory, as Bbltzmann had said, but one is not in sight yet: and Frank Smith is the only brave soul tackling this difficult problem.

The other interesting development over the last four years has been the considerable attention being devoted to 'the calm that follows the storm'. The possibilities of exploitation of the calm region trailing the spot, foreseen long ago by Schubauer and Klebanoff, are now being more quantitatively assessed.

The simpler situations in unsteady periodically-forced transitions are being sorted out. There is a big question regarding the disturbance environment in turbomachinery, and the proposed project on the subject was absolutely essential in his view. At the same time, as one moves deeper into the turbine and upstream wakes get chopped up, it is unlikely to be either necessary or desirable to follow each wake all the way through. Surely there must at some stage be a method of characterizing the disturbance environment statistically once again, although the statistics required would not be just the intensity, or even a length scale or a spectrum, but would have to be event-based: are there lumps of turbulence? at what rate do they arrive, how fat and intense are they? – and so on.

Transition models are now proliferating. Considering that even five to ten years ago there were only a few models around, growth has been rapid, and the subject is now becoming a minor industry. A major question that still remains is whether the models explicitly include the intermittency or not, and if they do whether it is treated as a parameter or as a dynarnical variable. Models now exist adopting each of these options. Narasimha confessed to a personal preference for physical, integral methods, where one sees exactly what is being done, in contrast to the more elaborate multiple p.d.e. systems, the reason being that ideas for control, management, manipulation, etc. are more obvious with the integral models. Of course the p.d.e. systems will perhaps integrate more easily with what is now being generally done with fully turbulent boundary layers, and if that route is followed, it would be essential in his view to follow the suggestion of David Ashpis and provide the designer with a presentation of the physics as well, so that he might be able to pick more intelligently the design options that should be explored. Whatever model is adopted, it is clear now that it would have to include unsteady transition as well.

Narasimha was of the firm view that it was only a matter of time before DNS would start to be used in a practical way, even though it was not going to be easy and may not be immediately achievable. The main reason far this view was that the Reynolds numbers in turbomachinery are relatively low: even $Re = 50{,}000$ is of direct practical interest. He predicted that the first major field in technology where DNS will make a direct impact will be turbomachinery. It was therefore prudent to prepare for the future, and if possible to make it happen: after all, computer power will probably have increased about a thousand-fold or more in 10 years' time. He did not want to suggest that the full turbine or compressor should be handled by DNS, but there were various bits of the system that in his view should be, keeping always the designer's needs in mind.

He referred to questions often raised about the possible relevance of stability theory in turbomachinery. At first sight stability would seem unlikely to be a major consideration because of the high disturbance environment, but various presentations made at the meeting showed that such a conclusion might be hasty. Reshotko's work on algebraic growth showed the importance of analysing transient disturbances. There was still the unresolved question about why e^n methods do not work as well on blades as on wings; Herbert had suggested several reasons that need to be investigated. Narasimha saw further use for the simpler alternatives that he and his colleagues at Bangalore had investigated. Questions of global and convective instability may play an important role in achieving a fuller understanding of the behaviour of separation bubbles and of near wakes, as Frank Smith had suggested.

Narasimha finally listed what appeared to him to be conspicuous gaps in the present research scene. There is first of all too little work on three-dimensional flows, too little DNS/LES (done specifically for turbomachinery flows), and too little theory, A coordinated project on a given blade row as more and more stages are mounted upstream – coordinating between experiments and computation, if not theory – seemed to him to be a great need. Along the line of the suggestions made by Ashpis, international programmes on the disturbance environment in turbomachinery and on DNS/LES would seem highly worthwhile; ERCOFTAC and Minnowbrook have shown how such international programmes can be organized. With the funding situation becoming so difficult, there seemed to be no alternative.

He concluded by thanking the organizers for putting together again such an interesting and pleasant meeting where industry, academics and government were all so well represented and interacted with such enthusiasm and frankness.

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