Technical Evaluation Report

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ABSTRACT

The following paper contains the report of the technical evaluator about the Specialists' Meeting mentioned above.

1.0 GENERAL REMARKS

Originally 34 papers were selected for the symposium. Six papers were withdrawn so that 28 papers were finally presented. Most of the papers exhibited a very high scientific level; some of them were even outstanding. The discussion of the papers was very lively whereas suggestions for future investigations were drawn up in a more reserved manner. The organization of the meeting was very good.

2.0 ESSENTIAL CONTRIBUTIONS OF DIFFERENT SESSIONS

2.1 Session 1: Subsonic Airfoil Flows

Two very interesting results were presented. It was shown that virtual aerosurface shapes could be produced by surface-mounted fluid actuators, for instance by a synthetic jet. Thereby the characteristic wavelength of the actuation is at least an order of magnitude smaller than the relevant local or global length scale in the flow. Therefore, the global effects are effectively decoupled from the actuation frequency. This virtual aero-surface shape was applied in two domains, i. e. at post-stall angles of attack and at small angles of attack. The authors could increase the lift with this procedure similar to the one observed in dynamic stall and could reduce aerodynamic forces.

In the next paper, drooping of the leading edge of airfoils was shown to possibly neutralize compressibility effects and minimize hysteresis effects of lift, pitching-moment and drag cycles of airfoils oscillating in pitch. When the Reynolds number is in a transitional range, the transition onset may move from very near the trailing edge at $\alpha = 0$ degrees to within a few percent of the leading edge at higher angles of attack. Such a large movement of transition has never been modeled in any computational study of the flow. A notable performance improvement was observed for all cases studied in the paper by optimizing the droop schedule that is the time history of the droop angle variation in relation of the angle of attack variation. It, however, would require a more detailed study of the effects of transition and separation. Nevertheless, turbulence models have failed up to now for strongly separated flows. If this problem could be solved the VDLE (variable droop leading edge) could be used to remarkably improve the performance of helicopter rotors and reduce vibration on these vehicles.

Some flow modeling for engineering computations was proposed to study instability and transition in a laminar separation bubble. The method was based on the Reynolds-averaged Navier-Stokes (RANS) equations and linear stability theory (LST). In the discussion, there were some doubts about the applicability of the combined procedure to unsteady flows.

Thus, the first session offered very interesting insights into some important mechanisms on laminar-turbulent transition and flow control. The results of these basic research papers have a great potential to be further developed in technology such as improving the performance of airfoils and ultimately, aircraft.

2.2 Session 2: Subsonic Separation Bubbles and Control

The contributions consisted primarily of numerical simulations using parabolic stability equations (PSE) and direct numerical simulations (DNS). By applying non-linear non-local instability analysis, it was shown that PSE is an appropriate tool for instability analysis of laminar separation bubbles up to moderately non-linear stages as long as the prevailing instabilities are convective. Even non-linear disturbance interaction scenarios that trigger laminar turbulent breakdown in transitional separation bubbles could be studied cost-effectively.

DNS was proven a very powerful tool to investigate the complex flow structures in a laminar separation bubble. Higher order difference schemes are certainly mandatory. In addition, application of DNS demands a lot of experience in using it properly. As pointed out in the discussion of one of the papers the results may be wrong if the code has too much diffusion. For instance, subharmonic breakdown should depend on 2-D amplitude and not on 3-D. If the code delivers a different result, it may have errors. Since transition affects separation, a code with problems of this kind may not be applicable to study separation control problems.

In further contributions of this session, the authors suggested some means of control of laminar separation bubbles by small amplitude 2-D and 3-D boundary layer disturbances. They demonstrated that an excitation of unsteady 2-D or 3-D disturbances is more advantageous than steady disturbances in separation control devices. To produce the necessary amplitude of an unsteady disturbance, they introduced one possible control system for laminar separation bubbles that consists of a frequency generator, an amplifier and an actuator. A broad band of frequencies in the most unstable frequency range could provide a robust signal source for the actuator.

Thus, based on a very deep study of the flow and transition mechanisms in subsonic separation bubbles using highly sophisticated simulation techniques, a variety of suggestions were presented in the2nd session on how to control separation bubbles and thus prevent increased drag and decreased lift. The application on how to influence the performance and flight mechanical stability of aircraft is thus obvious.

The **discussion at the end of the first day** ended with the following conclusions:

- Different kinds of separation bubbles can be globally or convectively unstable. This degree of impact on control effectiveness depends on whether the shear layer or the global mode dominates.
- Bubbles that are induced by strong or weak pressure gradients show so far little difference in the reverse flow although some other differences are exhibited between CFD and experimental results.
- Thin long bubbles have constant static pressure and low disturbances and represent the most typical case. Under certain circumstances, linear stability theory (LST) can be applied.
- Thick short bubbles exhibit large disturbance levels or large disturbances provided ahead of the bubble to keep it short. Even in this case, LST gives good growth rates when compared to DNS results. However, in this case local velocity profiles obtained by DNS must be used.

2.3 Session 3: Transition Prediction in Subsonic Flow

In the first paper of this session, an elegant method was presented to reduce the effort when calculating the huge number of eigenvalues to investigate N-factors. An adequate accuracy compared to an exact computation was obtained but the proposed method was roughly 2500 times faster than the exact computation.

Subsequent authors showed that present turbulence models could not predict the behavior of the flow at high angles of attack due to the underprediction of the trailing edge separation. They believe that transition models coupled with low-Reynolds number models or non-linear RANS models would improve the numerical results to predict the aerodynamic behavior of airfoils.

The authors of paper No. 10 offered a very detailed insight into the interaction of separation and transition of laminar separation bubbles in a 3-D boundary layer. They showed that the high amplification rates inside the separation bubble are not caused by the primary instability of the base flow. Instead, the amplification rates occur due to resonance and other non-linear effects as a direct consequence of the presence of the primary disturbances. For unswept models the first deviation from linear theory could be successfully described by secondary stability theory. However, for an increasing sweep angle there is also an increase of the amplification just inside the bubble, but a general decline of the global maximum amplitude level. The interesting result was that different types of instabilities act differently if there is a sweep angle or not. In addition, the authors showed that the quality of spatial linear stability theory (LST) is not affected with increasing sweep angle. The agreement with DNS results in the linear domain is as good as in unswept separation bubbles. The application of LST can therefore be recommended also for swept laminar separation bubbles in the first step of investigating the behavior of such bubbles.

A paper with corresponding experimental results was missing at this point of the session.

The next paper was aimed at designing and testing a 30-degree sweep laminar-flow wing for a high-altitude long-endurance aircraft. In order to form a basis for the design of swept wings, the authors discussed the fluid mechanical and geometrical parameters that influence transition both in free flight and in wind-tunnel experiment. They gave a special hint on how to advantageously use discrete roughness elements (DRE). They conducted wind tunnel tests with a wall liner to properly simulate full scale flow in their wind tunnel and showed that laminar flow over a 30 degree swept wing and testing of an "equivalent wing" in a low speed wind tunnel to compensate for Mach number reduction is possible. The authors demonstrated a remarkable extent of laminar flow to 50 % chord on the upper surface and between 70 % and 90 % on the lower surface. Thus, the Sensor Craft performance assumptions were verified, astonishingly without DRE.

2.4 Session 4: Surface Imperfections and Disturbances

Two classes of surface imperfections and their influence on laminar-turbulent transition were studied. The authors showed that backward facing steps cause very active perturbations with a laminar separation length of about 20 times the height. They also proved that tools based on viscous/inviscid strong coupling and stability theory lose their accuracy when separation occurs. More robust strong coupling approaches such as the multiple-scale techniques or Navier-Stokes codes are required. However, it has to be investigated whether normal turbulence models will be able to really simulate separation using Reynolds averaged Navier-Stokes Equations (RANS).

In paper No. 15, it was shown that natural surface roughness on the airfoil leading edge could have a detrimental impact on the airfoil performance. Key to this performance loss is the premature transition that is initiated by the roughness. The authors used DNS and obtained a steady separation region for a subcritical Reynolds numbers. A vortex evolves for supercritical Reynolds numbers. Dynamic roughness may suppress separation due to large angles of attack or rapid pitch-up and may delay the formation of the separation bubble. This could lead to an increase in airfoil performance.

Surface imperfections and disturbances are well-known objects that can influence the performance of airfoils and wings remarkably. Accordingly, it is very beneficial to study this kind of influence and investigate the tools available to simulate the influence of roughness elements.

2.5 Session 5: Turbomachines

In the first paper of this session, it was shown that transitional separation bubbles in an oscillating main flow exceed strong out-of-phase fluctuations. These are caused by the behavior of transition and reattachment, which do not appear to be synchronized with the main flow periodicity. A direct consequence of this phenomenon is the observation that the size of the bubble both in terms of thickness and length at any point in time is always smaller than for the corresponding steady flow bubble at the same Reynolds number. Thus, it was proposed to use this characteristic behavior in order to increase the length of the laminar boundary layer on the suction side of low-pressure turbine airfoils in order to reduce losses and improve efficiency. Generally, it was stated that superposition of some periodic unsteadiness could reduce the risk to have separation or incipient bursting unsteady flow. Further investigations were suggested.

Two separate but complementing computational approaches were introduced to review some of the physical mechanisms behind Active Flow Control (AFC) for Low Pressure Turbine (LPT) blade separation (Invited Paper 20). AFC by means of pulsed blowing through a slot increased the lift-drag ratio by 8%. The mechanism responsible for the increased performance of pulsed activations appeared to be related to the hydrodynamic instability of the underlying flow. The separated shear layer was shown to be unstable with regard to two-dimensional disturbances and the effectiveness of control and energy input required depended on the forcing frequency. For practical applications, it seemed advisable to deliberately force a large number of frequencies so that the flow can pick the most amplified frequencies depending on the operating conditions. In a second approach, a fundamental mechanism associated with steady and pulsed Vortex Generator Jets (VGJs) control was investigated using direct numerical simulations (DNS). Pulsed jets were found to reduce or prevent separation by a combination of two mechanisms, 1) accelerated bypass boundary layer transition and 2) development of strong spanwise coherent structures from natural hydrodynamic instability of the underlying flow. However, the authors indicated that the omitted effect of convex surface curvature be considered in future investigations.

Subsequently, instability results in the separation region of a flat plate, a NACA 0012 airfoil, and of a low-pressure turbine (LPT) blade were presented. The interesting result was the existence of bi-global eigenmodes pertinent to the separated flow region in all three flows. Although the authors showed some quantitative differences, there were similarities in the frequency and spatial structure of the velocity components of the disturbances of the most amplified global eigenmode. An additional result was that the instability characteristic of the dominant disturbances could be approximated by linear theory in the three cases considered. Finally, the authors showed that reconstruction of turbulent flow fields using empirical Galerkin reduced order models required the inclusion of instability information of the most unstable bi-global eigenmode.

The **final discussion of the day** led to the requirement to get improved closure models in CFD computations for turbulent flows and insight on how to control transition effects. The need for close cooperation between theoreticians, experts in numerical simulation and experimentalists was emphasized. This cooperation should occur early in planning investigations such as test campaigns. Throughout this discussion, the need for developing more reliable and accurate turbulence models was continually stressed.

2.6 Session 6: Transition and Separation in Hypersonic Flows

This was a very remarkable session. The first paper was an invited one entitled, "Hypersonic Boundary/ Shear Layer Transition for Slender to Blunt Configurations – Lessons Learned from Experiments," The authors emphasized the importance of laminar-turbulent transition on hypersonic configurations and showed the influence of boundary layer tripping in wind tunnel tests and the influence of protrusions from tile gap fillers on the Shuttle Orbiter. After having made some remarks on the possible cause of the Columbia fatal accident, they discussed the biggest impacts on vehicle design, such as the development of an experimentally derived hypersonic boundary layer transition criterion to predict hypersonic boundary-layer transition. These studies were also used to establish manufacturing step and gap tolerances for the thermal protection system (TPS). They discussed refinement of a wake closure correlation to blunt high-drag planetary entry vehicles that is an essential part of the TPS design process. Furthermore, they addressed the improvement of an engineering model to assess the thermal margin of the X-38 body flap in the presence of a separating and re-attaching laminar flow. An important contribution was the comparison of transition onset location between conventional and quiet hypersonic wind tunnels.

In the second paper of this session, the authors investigated the 2-D flow field with a laminar boundary layer free stream Mach number of 6 on which an oblique shock wave impinged, causing a laminar separation bubble. They showed that the resulting laminar shock/boundary-layer interaction increased the primary amplification of small-to medium-amplitude disturbances in the hypersonic boundary layer. Thereby, the primary instability is dominated by an increased amplification of the second Mack mode that is two-dimensional. They also confirmed experimental evidence that Görtler instability caused longitudinal vortices in the re-attachment zone of the shock-induced separation bubble. The growth rates of these vortices have been quantified for the first time. A comment from the audience was that there were more Görtler modes.

In the third paper of this session, the authors studied the separated flow field in the flap region of hypersonic re-entry vehicles. Heat loads induced by streamwise vortices in the transitional regime were considered with a structured RANS solver. The amplified vortices lead to a reshaping of the attachment line on the ramp. From these studies, a design process for re-entry vehicles could be derived to prevent vortex generation and accompanying heat flux peaks on deflected flaps. Thus, significant reductions of previous safety margins with respect to heat flux peaks should be possible in future designs.

This session impressively demonstrated progress in development of prediction tools and experimental simulation techniques to improve the design process of future space vehicles. The necessity was clearly emphasized that both theoretical/numerical and experimental investigations must be applied to reliably predict transition over transatmospheric space vehicles of complicated shape and protected by rough TPS surfaces. In addition, if there is an interest in space transportation systems or hypersonic vehicles in the future, the development of the technology and thus the accompanying research should be continued.

2.7 Session 7: Transition and Separation in Compressible Flow

The first paper of this session showed that self-sustained, low frequency oscillations could be created in a laminar boundary layer impinged upon by a shock wave. Below a critical incident shock angle θ the shock-wave/ boundary layer, interaction (SWBLI) remained 2-D and steady. When θ was larger than 31.7 degrees, there could be a steady 2-D and 3-D as well as an unsteady 3-D SWBLI configuration depending on the spanwise length of the shock wave. This successive process of bifurcation from a steady 2-D flow to an unsteady 3-D state occurred through intermediate steady 3-D but unstable states.

In the next paper, the authors investigated the growth and breakdown of localized disturbances into a turbulent spot in a Mach 2 boundary-layer flow. They used a localized blowing trip mechanism to trigger a turbulent spot in a laminar base flow. The study showed, besides the interesting flow structures, that compressibility suppressed the spot growth. Furthermore, the interaction of a turbulent spot with a shock-induced separation bubble enhanced the spot spreading and reduced the transition length.

The objective of a subsequent study was to cancel or at least to decrease aerodynamic instabilities, such as buffeting, by vortex generators (VGs) or trailing-edge deflectors (TEDs). The authors demonstrated that

VGs upstream of the shock decrease the separated flow zones, buffet level, pressure and shock fluctuations and even the separated flow noise. TED actuators increased the aerodynamic performance, delayed buffet onset and could be used when necessary. VGs are simpler, but decrease performance when there is no separation. TEDs require more complicated closed loop laws for dynamic control when applied in 3-D flows.

In the comprehensive paper No. 29, the authors successfully demonstrated the effectiveness of periodic Active Flow Control (AFC) at both model and full scale to reduce the download on the wings of the hovering XV-15 tiltrotor aircraft. With AFC and a Krueger flap, they could reduce the download by 20% in the model test and by 18% full scale. When using an additional micro adaptive flow control (MAFC) actuator to modulate the AFC frequency AFC, separation could be reduced and system energy loss could be lowered.

This session clearly demonstrated the transfer of technology to possible or even to existing applications.

2.8 Session 8: Massively Three-Dimensional Effects

In this session, an overview of the flow structures on a delta wing, both for laminar and turbulent flow, was presented and the behavior of the flow in the presence of a sharp and a rounded leading edge was discussed. The author especially addressed the new Vortex-Flow Experiment 2 (VFE-2) that is presently under way within the framework of the RTO AVT Task Group 113. He presented first and preliminary results of PSP (pressure sensitive paint) tests in the Transonic Wind Tunnel Göttingen (TWG). According to these experiments, the primary vortex formation on a wing with rounded leading edge is triggered by a twin vortex system emanating from a weak inboard-located laminar separation on the upper surface followed by a strong separation originating from the leading edge and located close to the leading edge. These results will help to improve current or to develop new simulation models.

The authors of the next paper showed that the flow structures both at the leading edge and turbulent separation lines above a straight wing are highly three-dimensional. The number of vortex pairs in the turbulent separation region on the wing surface depended on the angle of attack. They showed that surface humps could effectively control the structure of the vortices and change the topology of the 3-D flow. They expect that blowing might be more effective than humps.

In the last paper about flight-testing of laminar flow control in high-speed boundary layers, the problem of crossflow instabilities on swept wings was addressed. Differences in behavior of streamwise instabilities (T-S waves) and crossflow instabilities were emphasized. The authors could modify the mean flow in a nonlinear sense by applying micron-sized surface roughness. When they used a proper control wavelength, they expected to relaminarize large portions of an experimental wing on a test aircraft flying at supersonic speeds. Unfortunately, the flight-testing could not be completed according to the original plan.

The session impressively demonstrated how modern measuring techniques could provide possible new insights into the structure of separated flows and their impact on the performance and stability of aircraft.

3.0 CONCLUDING REMARKS AND OUTLOOK

During the final discussion on the last day of the meeting, the AVT-111 RSM Chair, Dr. Norman Malmuth, summarized the technical issues and presented some proposals for the possible continuation of AVT-111. These contributions were so perfect that there was scarcely the need for supplementary remarks of the technical evaluator. Thus, the outcome of the meeting may be summarized as follows.

Numerical simulation techniques, *e.g.*, direct numerical simulation (DNS), parabolic stability equations (PSE), large eddy simulation (LES), have already reached a high level of sophistication due to the enormous progress in theoretical knowledge, numerical methods and high performance computers. Although these methods are still restricted to simple generic models and to low Reynolds numbers they have already provided deep insight into the complex mechanisms of laminar-turbulent transition and the complex structures of laminar separation bubbles (LSB). Even first glances into the early stages of turbulent flows are possible. The meeting allowed also a survey of current work in the participating nations.

However, several technical issues remain unanswered. These include dependence of the aspect ratio, i.e., the height to length ratio, of LSB's on the scaling parameters as well as the usage of first-cut models based on vortex sheet inviscid approximations of viscous flows are open issues. Others involve the need to clarify the role of reversed flow in LSB's. Salient questions are: To what extent are PSE's as well as first and second order linear stability theories (LST) able to simulate the behavior of LSB's? What are the interactions inside and outside the LSB? What are the roles of free shear layers, Kelvin-Helmholtz instabilities, vortex pairing and wakes? How does separation interact with transition and what are the feedback loops?

It was demonstrated that unsteady effects play a major role in transition and separation. It was especially demonstrated that control of transition is more effective using unsteady effects, *e.g.*, unsteady blowing or jets, instead of steady means. This plays also a major role in the flow over blade elements of stators and rotors in turbomachinery.

Transition has a central importance in supersonic and hypersonic boundary layers as it influences drag and temperature distribution. There are even hot spots in the transition region due to the temperature overshoot between the laminar and turbulent part of the boundary layer. It is generally a very difficult task to test transatmospheric vehicles in wind tunnels. One can either simulate Reynolds number effects or high enthalpy effects. In addition, the noise produced by the turbulent boundary layer of the tunnel walls can remarkably influence the transition process on the actual model. Therefore, there is a demand for quiet tunnels. Additional problems of hypersonic vehicles such as capsules are their transitional wakes and shear layers.

Not only the numerical simulation of transition, shear layers and separation bubbles is a big problem but also experimental simulation. As soon as a probe is put into the transition region or in a wake, one can expect more or less severe disturbances of the flow. Therefore, optical non-intrusive diagnostics has gained big importance. Laser Doppler Anemometry (LDA), Particle Image Velocimetry (PIV), Stereo PIV (SPIV) and Particle Laser Induced Fluorescence (PLIF) have different spatial and temporal resolutions and must therefore be used in combination, sometimes even in combination with intrusive measuring devices, such hot wires.

Dr. Malmuth presented several proposals for continuation of AVT-111 as basis for discussion. He suggested the following objectives:

- Determine applicability of "lower order" methods to design transitional separated flow control schemes.
- Assess adequacy of instrumentation to spatially and temporally resolve transitional separation regions, e.g. bubbles.
- Identify, isolate and model key mechanisms unique to transitional separation.
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One may add:

- Investigate measures to improve the quality of so-called "quiet" wind tunnels.
- Improve the measuring techniques in short duration wind tunnels.

As an approach to reach the goal Dr. Malmuth suggested:

- Steady, low speed?
- Use German experiments and experimental capability as launching pad.
- Virtual electronically shared international database and geometry files.
- Triad of theory, computation and experiment.
- Decide whether basic or more practical orientation.
- Working group vs. periodic future specialist meeting.

Unfortunately, there was no open consensus on these approaches.