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A Comment Upon Previous Studies on 3-D Boundary Layer Transition

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Abstract: The common feature of the experimental studies upon 3-D boundary layer development on swept flat plates cited in the available literature is the application of streamwise and/or spanwise pressure gradients. In fact; presence of the pressure gradients was suggested to be vital for having crossflow effective in 3-D boundary layer transition. In the presented paper here, this idea is questioned evaluating the results of an experimental investigation conducted on swept flat plates under the absence of a pressure gradient. In this context the influence of plate sweep angle λ; itself on transition is determined simply through the natural transition measurements on the test plates with different λ .

Key Words: 3-D Boundary Layer, Transition

3-Boyutlu Sınır Tabaka Geçişi Konusunda Yapılmış Çalışmalar Üzerine Bir Yorum

Özet: Oblik hücum kenarlı düz levhalar üstünde gelişen 3-boyutlu sınır tabakalara ilişkin literatürde bahsedilen deneysel çalışmaların ortak özelliği akım doğrultusunda ve/veya akıma dik doğrultularda basınç değişimi uygulanmasıdır. Bir başka deyişle basınç uygulamaları sınır tabakanın türbülansa geçişinde etkin olan yanalakımı doğurması nedeniyle elzem bulunmaktadır. Sunulan makalede bu temel yaklaşım, oblik hücum kenarlı levhalar üstünde basınç değişimi uygulanmaksızın gerçekleştirilen deneysel bir çalışma sonuçları değerlendirilerek sorgulanmaktadır. Bu bağlamda levha hücum kenar açısının; λ türbülansa geçişteki etkisi basitçe farklı açılı test levhaları üstünde gerçekleştirilen doğal geçiş ölçümleri yoluyla belirlenmiştir.

Anahtar Sözcükler : 3 boyutlu Sınır Tabaka, Geçiş

Introduction

Since the early 1950's there has been considerable effort to understand the physics of boundary layer growth and particularly transition to turbulence on a swept wing. Boundary layer on a swept wing is refferred as a three-dimensional, 2-D one (Bradshaw 1984, Arnal 1986, Reed & Saric 1989). Streamwise instability governing the formation and growth of Tollmien-Schlichting (T-S) waves (Schlichting 1979), induces transition inside a 2-D boundary layer. While for a classical 3-D boundary layer on a swept wing, besides streamwise instability leading edge, centrifugal and crossflow instabilities influence the transition process. There exists a great number of theoretical and experimental studies investigating the interaction of crossflow and streamwise instabilities which were suggested to be the dominant instability modes on a swept wing.

Not only the flow on swept wings but also the flow on swept flat plates has been investigated by many researchers (Arnal & Juillen (1987), Müller & Bippes (1988), Dagenhart et al (1989), Itoh (1989), Mangalam et al (1990), Bippes & Nitschke-Kowsky (1990), and Agarwal et al (1992) to determine the different aspects of 3-D boundary layer transition. However in all of the studies conducted on swept flat plates streamwise and/or spanwise pressure gradients have been applied based on the fact that crossflow tending to an effective crossflow instability could be induced by means of the pressure gradients. However one can expect that boundary layer on a swept plate is no longer treated to be a 2-D one in the absence of pressure gradient due to the crossflow tending to an effective crossflow instability could be induced by means of the pressure gradients. However one can expect that boundary layer on a swept plate is no longer treated to be a 2-D one in the absence of pressure gradient due to the crossflow induced by its leading edge. Although it seems rather difficult to make a difference in the respective orders of importance of sweep angle and pressure gradients in the crossflow induction mechanism. Meanwhile except for the early works of Gray (1952) and Anscombe & Illingworth (1952) on swept wings, there is no study discussing the effect of the sweep angle, λ, upon boundary layer transition on a flat plate in the absence of a pressure gradient.

In the experimental investigation referred here (Çarpınlıoğlu, 1992) swept plates with sharp leading edges were used slightly tilted of the streamwise direction so that the stagnation front was located on the upper surface which significantly reduced the effect of leading ledge instability. Furthermore centrifugal instability was eliminated with the use of flat plates without any curvature to cause the formation of Göertler vortices. In fact Hall (1985) claimed that centrifugal instability was unimportant even in the concave region of swept wings. Therefore T-S waves and crossflow induced by leading edge of the test plates were seemed to be effective on the transition of the boundary layer. The influence of the sweep angle of the plate was investigated using the natural transition measurements conducted upon the test plates with λ covering a range of 0°, 10°, 20°, 35°, 50° in absence of a pressure gradient.

Experimental Setup

Wind Tunnel

The experiments were performed in an open circuit suction type subsonic wind tunnel. The test section of the tunnel has a 72 cm square cross section and a length of 250 cm. The free-stream turbulence intensity of flow, T is 0.2%.

Test Plate

The boundary layer flow was investigated on an aluminum flat plate (Figure 1) of width 71 cm, thickness 6 mm and long side length 180 cm. The leading edge of the plate was shaped to cover sweep angles 10°, 20°, 35° and 50° for each measurement set (Çarpınlıoğlu, 1992). The working surface of the plate was polished such that no roughness and unevenness could be felt to the touch of hand. The plate spanned the full width of the tunnel test section by bounding 5 mm rubber strips to felt its each side.

Measurements

The plates were tilted by -1.5° in order to bring the stagnation front onto their upper surfaces to eliminate the possibility of leading edge flow separation. Surface tufts and Kerosene vaporization technique were used to determine the stagnation front location. Zero streamwise pressure gradient was set by adjusting the

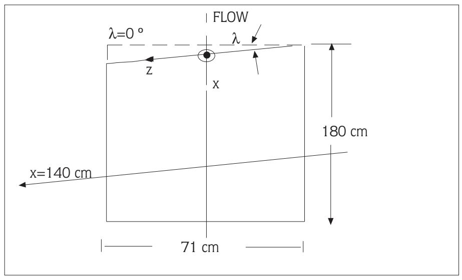

Figure 1 Top view of the test plate

false roof of the test section. Kerosene vaporization was also used to determine the measurement region on the test plate from the influence of boundary layers developing over the side walls of the test section.

The positions of the start and end of transition were determined from the dynamic head measurements (a methods suggested by Von Doenhoff) handled by Pitot and static pressure tubes. Pitot tubes of 1.1 mm, 1.59 mm external diameter and each with an internal to external diameter ratio of 0.6 were used. The tubes of 1.6 mm external diameter with two side holes of 0.5 mm diameter were used as static pressure tubes. Pitot and static pressure tubes were attached to the plate surface at the measurement station and free-stream speed was increased slowly. At each free-stream speed; dynamic head, h inside the boundary layer and reference free-stream dynamic head, Hr were recorded. Reynolds numbers for the start and end of transition, Rxs and Rxe were then calculated from the variation of h/Hr with Hr corresponding to the points at which slope of the curve h/Hr changes (Çarpınlıoğlu & Göksel, 1994).

It was known (Çarpınlıoğlu, 1992) that the magnitude and growth of crossflow inside the boundary layer on a swept flat plate changed with λ. However magnitudes of crossflow angles at the surface of the test plates were not high enough ($\alpha_w \leq 5°$) to influence the reading of surface pressure tubes. Therefore there was no significant error in transition determination by surface pressure tubes. Surface flow visualization with Kerosene vaporization was found to be not successfull for the transition region determination.

Results and Discussion

The natural transition on each test plate was determined within a span-6cm ≤ z ≤ +6 cm along a line which was parallel to the leading edge intersection the plate centerline at x=140 cm. The magnitudes of R_{xs} and R_{xe} on swept plates are less than those on the non-swept plate. The spanwise variation of R_{xs} and R_{xe} on the swept plates together with the corresponding data on the non-swept plate are shown in Figure 2. R_{xs} and Rxe on the non-swept plate don't vary much in spanwise direction. This is due to the two-dimensionality of the boundary layer for which only streamwise instability prevails. On the the 10º and 20º plates there exists a significant variation of R_{xs} and R_{xe} which is an indication of spanwise deformation of the boundary layer in the covered span. On the 35º plate almost a symmetrical variation of R_{xs} with respect to the plate centerline is observed. However the magnitudes of R_{xe} at z= -6 cm z= -4 cm are much lower than those at other spanwise locations on the 35º plate indicating earlier transition to turbulence locally. On the 50º plate, the dependency of R_{xs} and R_{xe} to spanwise location almost disappears with no apparent reason.

These observations imply that transition to turbulence on a swept plate has significant differences from that on a non-swpet plate even without a pressure gradient application. Furthermore on a swept plate transition is earlier than that on a non-swept plate with lower values of R_{xs} and R_{xe} due to the presence of crossflow. Since crossflow is induced by the leading edge of the plate, transition process on each test plate should have its own characteristics srongly influenced by the magnitude of the sweep angle.

The variation of R_{xs}, R_{xe} and $\Delta R_{xt}= R_{xe}-R_{xs}$ (defined as the transition length Reynolds number) with sweep angle, λ are evaluated on the centerline of the plates (z=0cm) (Figures 3a, 3b) to estimate the critical value of λ. Furthermore the observed % changes in R_{xs}, R_{xe} and ΔR_{xt} with respect to the corresponding ones one the non-swept plate are listed in Table 1. It is seen that R_{xs} has a drastical decrease with λ for λ <20º R_{xs} tends to an almost constant value of $R_{xs}=1.4x10^6$ with further increase in λ. The existence of a limiting value of R_x below which transition start is not seen on the swept plate points that magnitude of crossflow induced by the leading edge loses its influence on triggering transition for λ>20º. On the other hand R_{xe} which is not varying with λ in<35º shows a significant decrease for λ>35º. Furthermore maximum transition length Reynolds number, ΔR_{xt} is seen to occur at λ=20º and ΔR_{xt} at λ =50º is in the order of its magnitude determined at λ= 0º. This means that small lengths of transition can be expected for λ >20º is somewhat different from that on the ones with λ >20º.

Concluding Remarks

Although the presented study is based on limited experimental data on swept plates, it sets the importane of leading edge sweep itself upon boundary layer transition without a pressure gradient. Natural transi-

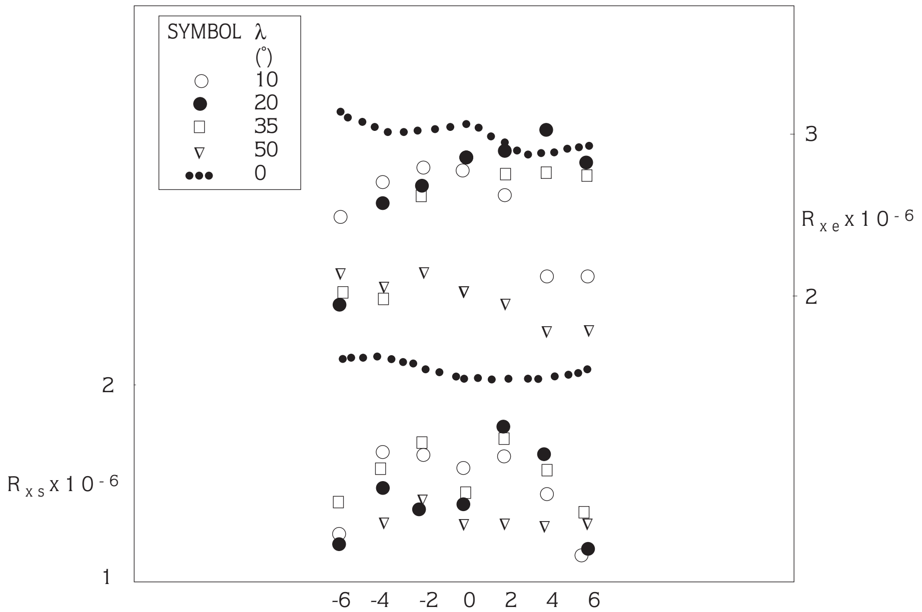

Figure 2. Spanwise variation of R_{xs} and R_{xe} t x=140 cm on swept plates.

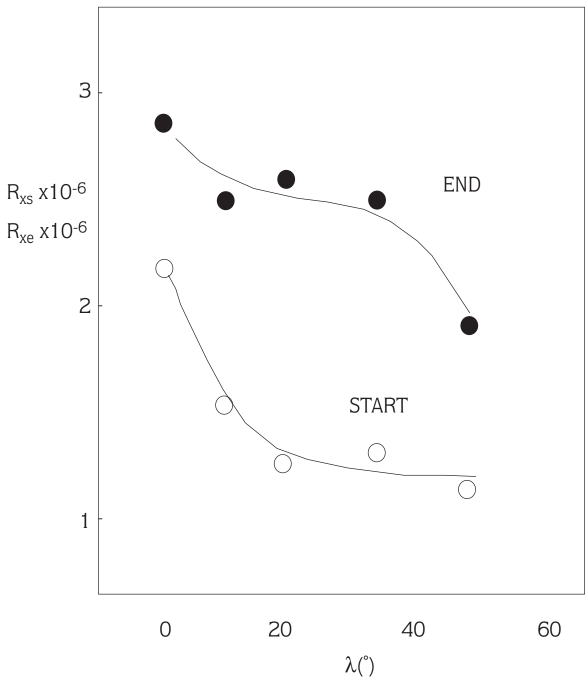

Figure 3a. Variation of R_{xe} and R_{xs} with λ

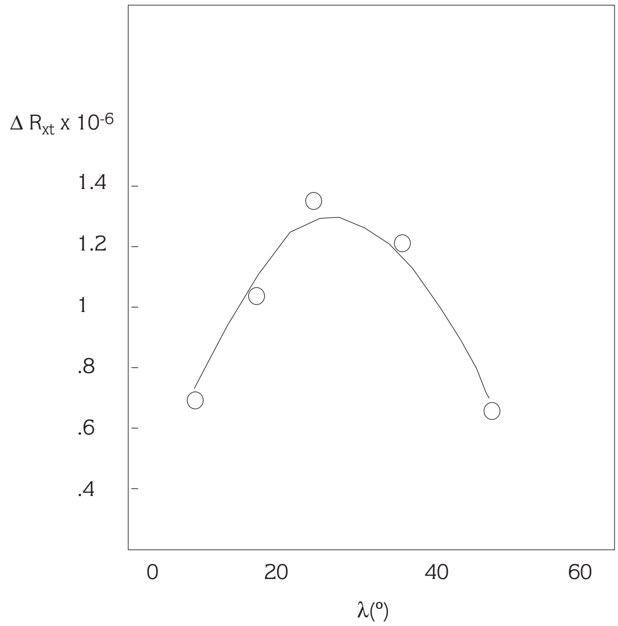

Figure 3b. Variation of Δ R_{xt} with λ

Table 1. Transition data at x= 140 cm, z=0 cm % change from the data corresponding to λ= 0º case

λ(º)	R_{xs} x 10^{-6}	R_{xe} x10^{-6}	ΔR_{xt} x10^{-6}	% in R_{xs}	% in R_{xe}	% in Δ R_{xt}
0	2.25	2.95	0.7	0	0	0
10	1.70	2.75	1.05	-24.4	-6.78	+50
20	1.5	2.86	1.36	-33.3	-3.0	+94.3
35	1.52	2.75	1.23	-32.4	-6.78	+75.7
50	1.38	2.05	0.67	-38.6	-30.5	-4.28

tion fronts measured on the test plate with different sweep angles, λ exhibit considerable deviation from that on a non-swept plate. Therefore boundary layer on a swept plate which is not a classical 2-D one has an early transition to turbulence due to the crossflow induced by its leading edge. The observed spanwise variations in R_{xs}, R_{xe} can be regarded as the indications of the three-dimensionality of the boundary layer which is induced by a possible spanwise deformation. However due to the non-linearity of the transition process itself, effect of λ on the start and end of transition seems to be rather different. Referring to the natural transiton fronts on swept plates and the values of R_{xs}, R_{xe} and ΔR_{xt} along the centerline of the plates the critical value λ appears to be 20º.

Finally it can be suggested that transition process on swept plates with $\lambda > 20^\circ$ is somewhat different from that on the ones with $\lambda \leq 20^\circ$.

Symbols

h Dynamic head measured by a surface Pitot tube inside the boundary layer

Hr Reference dynamic head measured by a Pitot tube outside the boundary layer

R_x Reynolds number based on streamwise length, Ux/v

R_{xe} R_x at the end of transition

R_{xs} R_x at the start of transition

Δ R_{xt} Transition length Reynold number, Rxe-Rxs

T Free-stream turbulence intensity, u'/U %

U Free-stream velocity, m/s

u' Turbulence velocity, x component

x Streamwise direction along the plate, cm

z Spanwise direction parallel to the leading edge of the plate, cm

α_w Crossflow angle at plate surface, degree

λ Sweep angle of the plate, degree

v Kinematic viscosity of air, m^2/s

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