Relaminarization of a Highly Accelerated Flow on a Convex Curvature

1Shital V. Patel, 2Ganesh Katke

1,2Bharati Vidyapeeth college of Engineering, Navi Mumbai
Email: 1virsh1974@gmail.com, 2ganeshkatke@asme.org

Abstract— Relaminarization of turbulent flow is a process by which the mean flow reverts to an effectively laminar state. The phenomenon of relaminarization in highly accelerated turbulent boundary layers on a flat plate has been studied in the past. Interest in the problem has recently revived because of aircraft design applications involving relaminarization at swept leading-edges at high-lift, both in flight and in wind tunnels. The analytical geometry and test parameters have been chosen, such as to provide conditions very similar to the real one. The analysis suggests that boundary layer thins down considerably during acceleration, thereby reducing the non-dimensional curvature parameter and consequently weakening the curvature effect i.e. curvature effects are weak once the flow is relaminarized. In summary, the analysis concludes that streamwise convex curvature can have surprisingly strong effects in promoting or aiding the relaminarization process of an accelerated turbulent boundary layer and this helps in the aerodynamic design of flight vehicles.

Index term - boundary layer flows, convex curvature, lift-coefficient, surface pressure distribution.

I. INTRODUCTION

The different mechanisms by which relaminarization may occur in these diverse situations are of three basic archetypes: (a) by dissipation of turbulence through the action of a molecular property like viscosity as in enlarging pipes/channels, (b) by destruction of turbulence due to a stabilizing body-force like buoyancy as observed in stable density-gradient flows and (c) by the domination of pressure forces as seen in severely accelerated turbulent boundary layers. The events leading to relaminarization include the breakdown of the law-of-the-wall with the velocity profile having a tendency to revert to the laminar profile, a significant decrease in the skin friction coefficient and an increase in shape factor towards laminar boundary layer values. Several authors have experimented and proposed that relaminarization is an asymptotic process involving a large ratio of the streamwise pressure gradient to a characteristic Reynolds stress, and developed a two-layer integral model (called the quasi-laminar equations, QLE) for predicting the mean flow parameters in the latter part of the relaminarization process. QLE are applicable for values of the pressure gradient parameter Λ (Narasimha and Sreenivasan’s pressure gradient parameter, Λ = \( \frac{\delta dp}{\tau dx} \) greater than about 50, but emphasized that this number is not to be seen as a ‘critical’ value. While early work on relaminarization was motivated by scientific curiosity, interest in the problem recent has revived because of aircraft design applications involving relaminarization at swept leading-edges at high-lift, both in flight and in the wind tunnels. Thompson [1973] appears to have been the first to suggest the possibility of relaminarization on swept wings. Relaminarization under such conditions can have considerable impact on airplane aerodynamics. Fig.1 shows a sketch of the possible variation of the maximum lift-coefficient (\( CL_{max} \)) with Reynolds number on a swept wing having a modern supercritical airfoil section. The attachment line can become turbulent under certain conditions and results in a loss of lift due to thicker boundary layers at the trailing edge. However, in the presence of strong acceleration around the wing leading edge at high-lift, the turbulent boundary layer may relaminarize leading to a certain recovery in the loss of maximum lift – the interplay between attachment line transition and relaminarizations, which are both Reynolds number dependent, can cause significant scale effects. It is known that convex curvature can have profound stabilizing effects on turbulence (Bradshaw [1969]). Hence, it is
likely that relaminarization at a swept wing leading edge is influenced by streamwise convex curvature in addition to strong acceleration. 2D experimental analysis systematically investigates the different effects on relaminarization, may therefore prove to be very useful for understanding many features of 3D relaminarization. This paper is essentially a delineation of proposed experimental analysis, where we analyze features of 2D relaminarizing boundary layer flows under the combined influence of acceleration and convex surface curvature at low speeds.

II. DELINEATION OF PROPOSED EXPERIMENT

Three relaminarizing boundary layer flows on the convex surface (designated CP1, DP1 and CP2), having different pressure gradient histories and different maximum values of the acceleration parameter K, is to be considered. The analysis is made for CP1, DP1 and FP1 consisted of surface pressure distribution along the model centerline, streamwise mean velocity and turbulence intensity profiles in the boundary layer assuming hot-wire probes, and mean and fluctuating components of wall shear stress using surface mounted hot-films at several streamwise stations. To provide an assessment of convex curvature effects on relaminarization, two strategies are to be adopted. First, additional proposed experimental analysis on a relaminarizing flow on a flat surface (designated FP1), with the conditions and pressure gradient history maintained very similar to the flow CP1, is to be made. Comparison of results of CP1 and FP1 will enable in identifying certain effects on relaminarization arising from convex surface curvature. Second, the usefulness and applicability of QLE for predicting the three relaminarizing flows on a convex surface is to be analyzed.

Proposed Experimental Set-Up

An attempt has been made to simulate certain important flow parameters similar to those on swept wing leading edges at high-lift, but in two dimensional flows. The experiment is to be performed in the 1.5m x 1.5m low-speed suction wind tunnel. The tunnel is assumed to be equipped with a variable speed DC motor which provides a free stream velocity up to 50m/s that can be controlled to better than 1%. The entrance to the tunnel is equipped with honeycombs and a set of three screens followed by a 12:1 contraction section. The uniformity of the tunnel flow mean velocity is to be better than 0.3%. The streamwise turbulence in the test section is to be quite low (varying from 0.06% to 0.11% in the velocity range of 10-50 m/s respectively).

Design Criteria

As the acceleration parameter K has been found to be useful to broadly indicate the occurrence of relaminarization at low speeds, in 2D flows a critical value of Kmax of about 3.5 x 10^6 has often been suggested to indicate the onset of relaminarization. Such suggestions have been based on observations of a variety of relaminarizing flows, in which the streamwise zone or duration of acceleration extended typically over 25-35δo (where δo is the initial boundary layer thickness), with the shortest extent being about 20δo in the flow. On swept wings at high lift, where relaminarization has been observed, the values of Kmax estimated along the external inviscid streamlines is as high as 10x10^6. Here the experiment is designed to provide different levels of Kmax on a convex surface. The region of acceleration is maintained relatively short in terms of the initial boundary layer thickness (<15δo), so as to reflect conditions similar to those encountered on swept wing flows. At the end of acceleration, a zone of moderate adverse pressure gradient is to be imposed so that the features of retransition, following relaminarization, are broadly similar to those on a swept wing. After an examination of the estimated values of curvature parameter (kδo) on swept wings, three flows have been investigated on the convex surface with different pressure gradient histories (i.e., K variations) and one flow on a flat wall. In order to bring out likely effects of pressure gradient histories on relaminarization, the above four flows have been chosen so that a suitably defined integral of the acceleration parameter, \( I(K) = \frac{1}{\delta_o} \int_0^{\infty} K dx \) has about the same value in all cases. Here xa is the distance from start to end of acceleration.

Description Of Model Geometry For Analysis

The geometric details of the two models used for the convex surface and the flat wall analysis respectively are described here.

Model for convex surface analysis :- The model configuration (Fig. 2) is used for the convex surface analysis, to be called 'curved-aft model', is a long and thick flat plate with an aft section having convex surface curvature. The flat section 0.8m long and 0.3m thick provides a thick and reasonably well developed turbulent boundary layer growing essentially at constant pressure. The convex rear section is 0.7m long having a radius of curvature of 0.967m; this radius is chosen to provide a nominal value of kδo of about 0.025. The upper surface of this curved-aft model is referred to as the “test surface”. The required favorable pressure gradients are imposed

Fig.2 Sketch for convex surface experiment
on the convex surface by locating a pressure-generator airfoil in its close proximity. The advantage of the airfoil is the flexibility it offers in generating a variety of pressure gradient histories, achieved by varying its location and incidence. The curved-aft model is assumed as a hollow wooden box with a smooth top surface made of glass fiber composite and is to be placed between 2D side-wall inserts located 0.6m apart. The inserts, spanning the top and bottom walls, is extend 0.5m

![Sketch for flat Surface experiment](image)

Fig.3 Sketch for flat Surface experiment

upstream of the model nose and 1.0m downstream of its trailing edge, in order to minimize any interference from the tunnel flow present outside the inserts. A 10mm gap on each end of the pressure-generator airfoil is to be made with a view to reduce the possible interaction of the side-wall boundary layer with the main flow. A horizontal splitter plate is to be added downstream of the trailing edge of the model to reduce possible upstream influence that may arise due to the merging of the upper and lower flows on the model. A wedge-like fairing is to be introduced in the trailing-edge region of the curved-aft section to reduce the severity of the associated adverse pressure gradient, and to avoid boundary layer separation that may otherwise be expected in the region. A 10mm band of rough emery paper, having a maximum height of approximately 1mm, is to be glued to the test surface at x= 0.24m to trip the boundary layer. The streamwise distance x is measured starting from the leading edge of the cylindrical nose, proceeding in the streamwise direction along the contour of the cylindrical section, the flat surface and finally the convex surface. The distance normal to the surface is designated y.

**Model for flat plate experiments:** - The model geometry to be used for relaminarization studies on a flat plate is shown in Fig.3. It consists of a flat plate section 0.04m thick, 2m long, and has a super-elliptic nose of ratio 5:1. It is to be placed between the two side-wall inserts located 0.6m apart, similar to the manner in which the model used for the convex surface. The pressure-generator airfoil spanned 0.58m.

**Instrumentation**

**Surface pressure measurements:** - The test surface to be used for the convex wall and flat plate relaminarization analysis is located typically 20mm apart along the centerline.

**Velocity and turbulent intensity profile measurements:** - The mean velocity and streamwise turbulent intensity profiles in the boundary layer should be measured at several streamwise locations on the test surfaces using a single hot-wire connected to a constant temperature anemometer (CTA). The hot-wire calibration can be expressed by a generalized King’s formula relating the wire voltage E to the normal velocity U as $E^2 - E_0^2 = AU^{1/n}$. Where $E_0$ is the no-flow voltage, and A and n are constants to be determined by calibration.

**Wall shear stress measurements:** - The mean and the fluctuating wall shear stress should be measured using hot-film gauges having a cold resistance of 50Ω, connected to the same CTA used for hot-wire measurements.

**Surface pressure distributions:** - The streamwise variations of the surface static pressure coefficient, $C_p$, for the three convex surface flows and flat surface are to be plotted and based on the measured $C_p$ distributions and the free stream velocity $U_{∞}$, the acceleration parameter K

$$(K = \frac{v^2}{U^2} \frac{dU}{dx})$$

of Launder [1964], the acceleration parameter $K^*$ ($K^* = \frac{v^2}{U^2} \frac{dU}{dx}$) of Brandt [1993], and the pressure gradient parameter $\Lambda$ ($\Lambda = -\frac{\delta dp}{T dx}$) of Narasimha and Sreenivasan [1973] to be calculated.

**Mean Flow Two-Dimensionality**

The two-dimensionality of the flow will be assessed by two methods as follows.

**Span wise pressure distribution:** - Show the results of measured $C_p$ distribution over the central mid-span of the model at some specific streamwise locations for CP1, DP1 and FP1.

**2D momentum integral balance:** - The two-dimensional momentum integral equation provides a tool for checking the two-dimensionality of the mean flow in the boundary layer. For a flat plate boundary layer, the equation can be expressed (by R. Mukund [2002]), in the form $\theta = \theta_n + \frac{1}{x} \left[ \frac{C_r}{2} - \left( H + 2 \right) \frac{\theta}{U} \left( \frac{dU}{dx} \right) \right] dx$, where $\theta_n$ denotes the value of $\theta$ at the initial x station. Here, all quantities on the right side are taken from measurements and the left side term $\theta_n$ is calculated and compared with the measured value. For assessing the momentum integral balance in the context of the convex surface flows, the above equation is to be used as an approximation, with streamwise distances measured along the curved wall, and the velocity calculated from the surface pressure is to be used for normalizing the wall shear stress (measured using hot-films) and also for the determination of the
streamwise velocity gradient \( \frac{dU}{dx} \). The comparisons of the calculated values of the momentum thickness with the experiments should also be plotted.

### Results of Analysis

The results of the measurements to be made on the convex surface (CP1, DP1 and CP2) and on the flat surface (FP1) can be presented through the mean flow parameters is to be presented first, followed by a presentation of turbulence intensity profiles and the fluctuations of velocity and shear stress.

#### Mean velocity profiles

- The boundary layer streamwise mean-velocity profiles measured using a hot-wire at different \( x \) locations are presented in for CP1, DP1 & FP1 and show a plot of \( U/U_o \) (\( U_o \) being the edge velocity in the upstream constant pressure region at \( x = 0.8m \)).

#### Boundary layer parameters – definitions

- The definitions of the integral thickness parameters usually adopted for curved surface boundary layers are (from Sø & Mellor [1972]):

\[
\delta^* = \int_0^\delta \left(1 - \frac{u}{U_p}\right) \, dy; \quad \text{Momentum thickness}\]

\[
\theta = \int_0^\delta \frac{u}{U_p} \left(1 - \frac{u}{U_p}\right) \, dy; \quad \text{Shape Factor}\]

- The streamwise distance from the leading edge of a swept wing at high lift as well as to provide a data base for modeling the flow, the delineation of proposed experiment on relaminarization under the combined action of acceleration and streamwise convex curvature is to be conducted at low speeds. Three relaminarizing boundary layer flows on the convex wall are to be analyzed along with comparison has to be made with a relaminarizing flow on a flat plate. In summary, the results to be obtained for examining the effects of convex surface curvature on relaminarization, and the detailed comparisons of the data with predictions based on QLE, would have to be taken into account in assessing the effects of possible relaminarization on swept wings in the aerodynamic design of flight vehicles. The main motivation for this proposed 2D experiment is an initial exploration in understanding 3D relaminarization on swept wings in flight.

#### Calculations Of The Relaminarized Flows

It may be noted that different approaches are needed to calculate the complete flow, consisting of calculation regimes. The relaminarizer zone is to be calculated here using the quasi-laminar equations (QLE). Since there are no methods known for the calculation of the relaminarization of accelerated turbulent boundary layers on a curved surface, we have to use QLE, without any modeling for curvature effects, in calculating the later stages of relaminarization on the surface.

#### Comparison Of The QLE With The Present Experimental Data

We compare the predictions of \( C_f \) and \( R_\theta \) calculation zones with measured values for CP1, CP2, DP1 and FP1.

#### Location Of Retransition

An attempt can be made to explain the delay in retransition using the inner laminar-layer solution of QLE. In our case, the value of the momentum thickness Reynolds number \( R_\theta,i = \frac{\theta U_s}{\nu} \) (where \( \theta \) refers to the momentum thickness of the inner layer and \( Us = u(x) \) is the velocity on the streamline which separates the inner and outer layers) is to be calculated using the inner laminar-layer solutions of the quasi-laminar calculations at the \( C_{min} \) location for several relaminarization experiments.

### III. CONCLUSION

With a view to understand relaminarization near the leading edge of a swept-wing at high-lift as well as to provide a data base for modeling the flow, the delineation of proposed experiment on relaminarization under the combined action of acceleration and streamwise convex curvature is to be conducted at low speeds. Three relaminarizing boundary layer flows on the convex wall are to be analyzed along with comparison has to be made with a relaminarizing flow on a flat plate. In summary, the results to be obtained for examining the effects of convex surface curvature on relaminarization, and the detailed comparisons of the data with predictions based on QLE, would have to be taken into account in assessing the effects of possible relaminarization on swept wings in the aerodynamic design of flight vehicles. The main motivation for this proposed 2D experiment is an initial exploration in understanding 3D relaminarization on swept wings in flight.
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