EFFECTS OF PERIODIC UNSTEADY WAKE FLOW AND PRESSURE GRADIENT ON BOUNDARY LAYER TRANSITION ALONG THE CONCAVE SURFACE OF A CURVED PLATE

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ABSTRACT

Boundary layer transition and development on a turbomachinery blade is subjected to highly periodic unsteady turbulent flow, pressure gradient in longitudinal as well as lateral direction, and surface curvature. To study the effects of periodic unsteady wakes on the concave surface of a turbine blade, a curved plate was utilized. On the concave surface of this plate, detailed experimental investigations were carried out under zero and negative pressure gradient. The measurements were performed on an unsteady flow research facility using a rotating cascade of rods positioned upstream of the curved plate. Boundary layer measurements using a hot-wire probe were analyzed by the ensemble-averaging technique. The results presented in the temporal-spatial domain display the transition and further development of the boundary layer, specifically the ensemble-averaged velocity and turbulence intensity. As the results show, the turbulent patches generated by the wakes have different leading and trailing edge velocities and merge with the boundary layer resulting in a strong deformation and generation of a high turbulence intensity core. After the turbulent patch has totally penetrated into the boundary layer, pronounced becalmed regions were formed behind the turbulent patch and were extended far beyond the point they would occur in the corresponding undisturbed steady boundary layer.

NOMENCLATURE

\( N \) = total number of samples of hot-wire data for time-averaging or total number records for ensemble-averaging
\( m \) = number of hot-wire samples taken per revolution of the wake generator
\( r \) = radius of curvature of the curved plate, 702.5 mm
\( \text{Re} \) = Reynolds number, \( \text{Re} = \frac{U h}{v} \)
\( s \) = longitudinal distance from the plate leading edge
\( s_0 \) = arc length of plate, 690 mm
\( t \) = time
\( Tu \) = reference turbulence intensity, \( Tu = \frac{\sqrt{u'^2}}{U_{in}} \times 100 \)
\(<Tu>\) = ensemble-averaged reference turbulence intensity
\( Tu_{loc} \) = local turbulence intensity, \( Tu_{loc} = \frac{\sqrt{u'^2}}{U} \times 100 \)
\( u \) = turbulent fluctuation velocity
\(<u>\) = ensemble-averaged fluctuation velocity
\( U \) = time-averaged mean velocity
\( U_{ref} \) = reference velocity for each particular boundary layer traverse
\( U_m \) = mass-averaged velocity
\( y \) = lateral distance from plate surface
\( \delta \) = momentum thickness
\( \theta \) = angular position of the probe location from the inlet
\( v \) = kinematic viscosity of air
\( \rho \) = density of air
\( \tau \) = one wake passing period, 40 ms

Subscripts
ref = reference
loc = local
in = inlet to test section

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INTRODUCTION

The flow in a turbomachinery stage changes the frame of reference from an absolute frame, represented by the stator cascade, to a relative rotating one, specified by the rotor cascade. As the flow passes through a cascade, the viscous boundary layer flow near the suction and pressure surfaces of the blade undergo a laminar-turbulent transition. After completing the transition process, the turbulent boundary layer is further developed until the trailing edge plane is reached. During this process, the viscous flow experiences a momentum defect associated with energy dissipation (Schobeiri, 1989). The boundary layer thicknesses on the suction and pressure surfaces, together with the trailing edge thickness, in association with the rotational motion of the blade, generate an unsteady wake region that characterizes a periodic unsteady inlet flow to the following cascade. The mean velocity in the wake region is superimposed by turbulent fluctuations. Due to the frame of reference change, the following cascade is exposed to periodic unsteady inlet flow that affects the boundary layer flow pattern, velocity, pressure, shear stress distribution and, particularly for cooled blades, the heat transfer characteristics.

The comprehensive investigations by Walker (1974, 1982, 1989), Walker and Gostelow (1990), Evans (1978, 1982), Lakshminarayana and his co-workers (1976, 1980, 1981a, 1981b, 1983), Sudder et al. (1987), and Hathaway et al. (1987), among others, study the effect of flow parameters such as unsteadiness and turbulence on the compressor stage flow field. These parameters also have a significant impact on turbine design, specifically the aerodynamics and heat transfer, as demonstrated by Hodson (1984a,b), Hodson and Addison (1989), Blair (1983), Blair et al. (1988), Dring et al. (1982, 1986), and Joslyn et al. (1983). These investigations have significantly contributed to better qualitative understanding of unsteady flow phenomena. However, their results incorporate the influence of interactions between several machine specific parameters which do not allow for deduction of quantitative conclusions required for establishment of turbulence and transition models applicable to turbomachinery flows. In addition, the small geometric dimensions of a turbine or compressor blade make flow measurements near the wall, particularly the boundary layer measurement, an extremely difficult task. This circumstance may partially explain the reason for the lack of relationships that accurately describe the turbomachinery unsteady flow physics, particularly, the boundary layer transition phenomenon. The prediction of the boundary layer transition under turbomachinery flow conditions, particularly the transition start and length, is one of the most critical issues in turbomachinery flow research. It is of particular significance to heat transfer and wall shear stress calculations as pointed out recently in an extensive discussion by Walker (1993). As shown by Gaugler (1983), Schobeiri et al. (1991), and in a recent comprehensive study by Mayle (1991), the existing correlations by Abu-Ghamamm and Shaw (1980) and Dhawan and Narasimha (1957), among others, used for aerodynamic design of aircraft, are not capable of correctly predicting the transition behavior which is essential for accurately calculating the heat transfer coefficient of gas turbine blades.

PERIODIC UNSTEADY FLOW SIMULATION

The complexity of the unsteady flow situation and lack of appropriate experimental data necessary for the generation of corresponding transition and turbulence models have motivated several researchers to establish programs for simulating periodic unsteady flow and quantitatively studying its effects. By using a rotating cascade of rods for the generation of periodic unsteady wakes and employing test objects that allow convenient measurement of the boundary layer parameters, researchers are better able to study the unsteady flow phenomena.

Earlier studies by Reichardt (1950) indicated the structural similarity between the cylinder and the blade induced wake turbulence quantities. This issue was investigated later by several investigators including Eksler (1974) and Pfeil and Eksler (1975a,b), among others. They concluded that the use of rotating rods instead of rotor blades is appropriate, since the turbulence characteristics of the cylinder wake flows, in terms of Reynolds stress components, are similar to those of rotor blade wakes. This is particularly true for relative distances 1/d > 80 ("far wake"), where s is the streamwise distance and d is the rod diameter.

The measurement of mean velocity, turbulence intensity, and Reynolds stress downstream of a compressor cascade by Raj and Lakshminarayana (1973) demonstrated that the turbulence characteristics are asymmetric with respect to the wake center. A similar asymmetric pattern is also encountered in the wake downstream of a cylinder within the curved channel studied by Schobeiri et al. (1993). Their studies show that the mean velocity defect, the turbulence intensity in longitudinal and lateral directions, as well as the turbulent shear stress distribution are asymmetric. This asymmetric behavior is due to the asymmetric velocity distribution upstream and a non-zero pressure gradient in lateral direction downstream of the cylinder. Schobeiri et al. (1993) created the theoretical framework for precise prediction of steady and unsteady wake development through a curved channel.

Pfeil and Pache (1977) and Pache (1976) simulated periodic unsteady inlet flow and studied its influence on boundary layer development under adverse and favorable pressure gradients. They utilized a wake generator with a series of cylindrical rods arranged circumferentially on two parallel rotating disks positioned upstream of the test objects. Similar wake generators are used by Pridy and Bayley (1988) and Liu and Rodi (1989, 1991) for heat transfer and boundary layer investigations. Using a flat plate and a NACA-65010 airfoil as test objects for boundary layer investigations, Pfeil and Pache (1977) concluded that the existing calculation methods based on experiments with an artificially increased stochastic turbulence level of the external flow are poorly applicable to their test cases. In continuation of the above research work, Pfeil and Herbst (1979), Herbst (1980), and Pfeil et al. (1983) concentrated their efforts on investigating the transition process of unsteady boundary layers. Using a flat plate and varying the pressure gradient and the unsteady inlet flow condition, by changing the number, diameter, and frequency of the rods, Pfeil et al. generated wake induced transition, where intermittent laminar and turbulent states of the boundary layer were observed. Their studies show that the wakes generated by the rods affect the onset and length of transition, particularly if the flow is subjected to a favorable pressure gradient. With the test facility described above, Pfeil and his co-workers initiated an innovative experimental program with a long term objective of quantifying the transition process. Using the flat plate data by Pfeil and Herbst, the turbine data by Dring et al. (1986), and the cascade data by Wittig et al. (1988), Mayle (1991) created a correlation for intermittency distribution that describes the entire range measured by Pfeil and Herbst (1979) and Herbst (1980).
The above boundary layer research program by Pfeil was continued very recently by Orth (1991, 1992), whose comprehensive research work deals with the boundary layer transition on a flat plate periodically disturbed by wakes. Orth found that boundary layer flow periodically disturbed by wakes differs in two ways from a boundary layer developing in undisturbed flow. First, an early onset of transition is observed momentarily as the high turbulence level of the wake disturbs the boundary layer and leads to the formation of turbulent patches. Second, laminar bumbled regions are formed behind the turbulent patches, so that brief periods of laminar flow are still observed beyond the location at which the steady flow boundary layer is fully turbulent.

Despite the intensive efforts to understand the transition phenomenon on flat plates, there are no significant experimental or theoretical investigations that show the effect of the unsteady inlet flow condition on the transition process on a convex or concave curved surface. Experimental studies concerning the influence of curvature on internal flows by Baskaran et al. (1990), Hoffman et al. (1985), Muck et al. (1985), Gillis and Johnson (1983) and the theoretical investigations by Schobeiri (1976, 1980, 1990) show the effect of curvature and pressure gradient on boundary layer, velocity, and temperature development. However, those investigations do not encompass the unsteady flow parameter. Since the above parameters determine the performance of a high efficiency turbomachinery stage, there has been an urgent need for turbine and compressor designers to understand and quantify the effects of these parameters. To address these issues, Schobeiri (1988), initiated a comprehensive research program and established the necessary research facility for investigating the effects of unsteady inlet flow, pressure gradient, and curvature on boundary layer transition, wake development, and heat transfer. The periodic unsteady flow is established by a wake generator with a series of cylindrical rods arranged circumferentially on two parallel rotating discs, similar to Pfeil's facility. Experimental studies of steady and unsteady wake development, as well as the investigations of the effect of periodic unsteady inlet flow, curvature, and pressure gradient on boundary layer transition, are currently being executed. The preliminary experimental investigations by Schobeiri and Pardivala (1992), in accordance with those reported by Liu and Rodi (1991), have shown that by correct adjustment of the plate location as well as the proper choice of the number of cylindrical rods, very clean periodic unsteady flow can be established which allows precise time dependent boundary layer measurement.

**EXPERIMENTAL RESEARCH FACILITY**

The test facility consists of a large centrifugal fan, a settling chamber, a nozzle, a wake generator, a test section, and an exit duct (see Fig. 1). The centrifugal fan is driven by a 112 kW 3-phase AC motor operating at its rated speed. At the test section, the fan generates a mean velocity of 36 m/s and a maximum Reynolds number (based on the test section inlet height) of 8.8 x 10^6. The flow entering the fan passes through a 50 mm thick fiber glass filter capable of filtering particles of up to 5 μm. A Prandtl probe is permanently located in the straight pipe, upstream of the diffuser, to sense any fluctuations in the mean velocity resulting from fluctuations in the fan speed.

A short diffuser is located downstream of the straight pipe and decelerates the flow before it enters the settling chamber. The settling chamber is made of three sections each of length 750 mm, and cross-section 1200 mm x 820 mm. Four screens and one honeycomb flow straightener are used to control the flow uniformity and turbulence level within the settling chamber. The free stream turbulence intensity can be controlled by the number of screens, their mesh size, and the open area ratio. With this configuration it was possible to establish a very uniform velocity profile and a free-stream turbulence intensity of 1.2 percent at the inlet of the test section without the wake generator. Downstream of the settling chamber is a nozzle, with an area ratio 4:1, to accelerate the flow to the required velocity before it enters the wake generator. The nozzle establishes a smooth transition of the flow from the settling chamber to the wake generator.

For the simulation of the unsteady inlet flow condition and the wake flow pattern downstream of a rotor row, the wake generator of Fig. 2 is utilized, whose cross-section is displayed in Fig. 3. The wake generator can incorporate up to 30 cylindrical rods (spokes) that are arranged circumferentially on two parallel rotating disks. The disks can rotate clockwise as well as counter-clockwise. However, in order to simulate the rotor-stator wake interaction within a turbomachinery stage, the disks are rotated in the counter-clockwise direction looking from the point of view shown in Fig. 2. To avoid the inception of undesirable secondary vortices generated by the rotating disks, the disks are covered by two stationary circular disks connected with the inner shaft (Fig. 3). In order to simulate the wake width and spacing, the diameter and number of spokes can be varied. For the present investigation, five rods with a diameter of 2 mm were used. As shown in Figs. 2 and 3, the rotating disks are driven by a frequency controlled electric motor with a belt transmission, a maximum power of 7.45 kW (10 hp), and a maximum rotational speed of 1750 rpm. A fiber-optic sensor directly monitors the angular frequency of the wake generator. The sensor also serves as the triggering mechanism for data transfer and its initialization needed for ensemble averaging.

The test section, shown in Fig. 2, is located downstream of the wake generator and consists of a convex top wall, a curved plate for boundary layer measurements, a concave bottom wall and two vertical transparent acrylic side walls. In addition to simulating convex curvature, the convex wall assembly is designed to allow precise radial and circumferential traversing of the probes.

For the boundary layer investigations, a curved plate of 690 mm arc length and 593 mm width with a leading edge radius of 1 mm and a constant curvature radius of 70.5 mm is inserted in the mid-height of the test section in Fig. 2. The curved plate, having smooth surfaces, incorporates static pressure ports mounted flush with the surface at arc length spacings of 36.8 mm. The ports are connected to a manometer bank for visualization purposes, specifically for cases where a leading edge flow separation may occur. The plate is mounted between the two plexiglass side walls, where its axial and angular position can be precisely varied by a positioning system consisting of a plexiglass disk, in which the curved plate is mounted eccentric to the center, and two angular verniers shown in Fig. 2. This positioning system allows variation of the pressure gradient and the fine adjustment of the leading edge position to avoid inception of separation bubbles.
Fig. 1 Overall layout of the test facility: 1-fan; 2-motor; 3-transition duct; 4-straight pipe; 5-diffuser, 6-settling chamber; 7-nozzle; 8-wake generator; 9-test section; 10-exit duct.

Figure 2. Test section, 1-traversing system, 2-vernier, 3-nozzle, 4-wake generator, 5-electric motor, 6-convex wall, 7-exit duct, 8-concave wall, 9-hot-wire probe, 10-plexiglass wall, 11-curved plate, 12-large vernier, 13-small vernier.
The data acquisition system is controlled by a personal computer, in which a 12-bit A/D (analog to digital conversion) is installed. The instantaneous velocity signal is obtained using a constant temperature hot-wire anemometer system (TSI IFA100). Each channel of the anemometer system has a signal conditioner with variable low and high pass filters, DC-offset, and adjustable gain. Based on numerous spectral measurements within the wake, the low pass filter of the signal conditioner is set to 20 kHz. All the measurements in the present study were made using a tungsten hot-wire sensor of 4 μm in diameter mounted on a custom designed single-wire boundary layer probe.

For unsteady boundary layer measurement, a high response reflective type, fiber optic proximity sensor (ATC 7062A), located close to the pulley of the wake generator produces a signal once a revolution. The signal is sent when a piece of reflective tape fixed on the pulley comes across the proximity sensor. The signal generated from the fiber optic sensor is converted to 0-5 V level and is transferred to the Schmitt-trigger inputs of two monostable multivibrator circuits with adjustable output pulse width. The signal trigger system is used for starting data collection and tracking the number of cycles to later aid in the calculation of the ensemble-averaged quantities of the periodic unsteady wakes. A photoelectric proximity sensor with a digital readout is used to display the angular velocity of the centrifugal fan.

Accurate measurement of the data presented in this paper requires calibration of the hot-wire sensor. In order to ensure a high level of accuracy, the calibration facility described in John and Schobeiri (1993) was used for all hot-wire calibration. For the data reduction and analysis, the characteristic response of the hot-wire probe is stored in the form of calibration coefficients. The instantaneous velocity components are calculated from the temperature compensated instantaneous voltages using the calibration coefficients. The instantaneous velocity can be represented in the following form.

\[ U = \bar{U} + u \]  

Where \( \bar{U} \) is the mean (time averaged) velocity and \( u \) is the turbulent fluctuation component. The mean velocity, also known as the time-average, is given by

\[ \bar{U} = \frac{1}{N} \sum_{j=1}^{N} U_j \]  

where \( N \) is the total number of samples at one radial location. A sampling rate of 1 kHz was used for the investigation of steady flow (no wakes). Good convergence was found for \( N=16384 \) samples. The root mean square value of the turbulent velocity fluctuation is obtained from the instantaneous and mean velocity by

\[ u = \sqrt{\frac{1}{N} \sum_{j=1}^{N} (U_j - \bar{U})^2} \]  

and the local turbulence intensity is defined as

\[ Tu_{\infty} = \frac{u}{U} \times 100 = \frac{1}{U} \sqrt{\frac{1}{N} \sum_{j=1}^{N} (U_j - \bar{U})^2} \times 100 \]
For certain presentations of the turbulence intensity it is appropriate to non-dimensionalize with respect to a reference velocity for a particular boundary layer. This reference turbulence intensity is given by

\[ Tu = \frac{\bar{u}}{U_{ref}} \times 100 \]

(5)

As previously mentioned, the data acquisition for the unsteady wake flow was triggered by a once-per-revolution signal from a fiber optic proximity sensor. The unsteady data were reduced by the ensemble-averaging method. 256 samples were taken for each of 400 revolutions of the wake generator at each radial position. Since the wake generator had five rods, 400 revolutions of the wake generator produced 2000 near and 2000 far periodic wakes. The data were ensemble-averaged with respect to the rotation period (200 ms) of the wake generator. Thus, the ensemble-averaged results calculated over the 400 revolutions show five wake passes. Variation of the number of samples per revolution and number of total revolutions were performed to determine the optimum settings for convergence of the ensemble averaging.

The ensemble-averaged fluctuation velocity and the turbulence intensity are calculated from the instantaneous samples by:

\[ \langle U(t) \rangle = \frac{1}{N} \sum_{j=1}^{N} U_j(t) \]

(6)

\[ \langle u(t) \rangle = \frac{1}{N} \sum_{j=1}^{N} [U_j(t) - \langle U(t) \rangle]^2 \]

(7)

\[ \langle Tu(t) \rangle = \frac{\langle u(t) \rangle}{U_{ref}} \times 100 \]

(8)

where \( j=1,2,..,N \), and \( N \) is the total number of periods (i.e. 400 revolutions), and \( i=1,2,..,m \), where \( m \) is the number of samples taken per period (\( m=256 \)). \( U_{ref} \) is the reference velocity for the particular boundary layer traverse.

For data reduction and analysis, a FORTRAN code was developed and executed on a 486DX personal computer.

MEASUREMENTS, RESULTS, DISCUSSIONS

Boundary layer transition and development along the concave side of the curved plate, shown in Fig. 2, under periodic unsteady flow conditions was experimentally investigated for zero and negative pressure gradients. The reference boundary layer configurations with steady flow (no wakes) were studied for both pressure gradients. The streamwise distributions of the non-dimensional freestream velocities at a constant lateral position of \( y = 30 \) mm above the plate surface are shown in Fig. 4. The zero-pressure gradient freestream velocity exhibits a constant value along the major portion of the plate length. Close to the plate trailing edge, the freestream increases due to a minor blockage of the channel cross section caused by boundary layer growth of the side walls as well as the curved plate. The freestream velocity pertaining to the negative pressure gradient case continuously increases from the plate leading edge at \( s/s_n = 0 \) to the trailing edge at \( s/s_n = 1 \).

![Figure 4](http://nondestructive.asmedigitalcollection.asme.org/GT/proceedings-pdf/GT1994/78835/V001T01A106/2404670/v001t01a106-94-gt-327.pdf)

**Figure 4.** Non-dimensionalized mean freestream velocity at \( y = 30 \) mm above the plate surface.

![Figure 5a](http://nondestructive.asmedigitalcollection.asme.org/GT/proceedings-pdf/GT1994/78835/V001T01A106/2404670/v001t01a106-94-gt-327.pdf)

**Figure 5a.** Inlet velocity distribution non-dimensionalized with respect to the mass-averaged velocity for three different Reynolds numbers.

![Figure 5b](http://nondestructive.asmedigitalcollection.asme.org/GT/proceedings-pdf/GT1994/78835/V001T01A106/2404670/v001t01a106-94-gt-327.pdf)

**Figure 5b.** Inlet local turbulence intensity for three different Reynolds numbers.
To clearly define the inlet flow condition of the test section in the absence of the wake generation rods and the curved plate, the velocity and turbulence intensity distributions were measured immediately at the inlet to the curved test section, where the curvature starts. Fig. 5a shows the non-dimensional velocity distribution in the lateral direction for three different Reynolds numbers, Re = 4.6 \times 10^4, 6.0 \times 10^4, and 8.8 \times 10^4. The typical asymmetric distribution of the velocity, with higher magnitude on the convex wall and lower magnitude on the concave wall, is due to the start of the curvature in the test section. Further information concerning the inlet flow profile is provided by measuring the turbulence intensity distribution. Fig. 5b exhibits the distribution of the local longitudinal turbulence intensity with a freestream value of 1.2 percent for three different Reynolds numbers, Re = 4.6 \times 10^4 and 6.0 \times 10^4.

Steady Boundary Layer at Zero Pressure Gradient

Starting with the zero pressure gradient case, the reference profile is measured under steady flow condition (i.e. no wakes). The boundary layer quantities such as velocity and turbulence intensity are measured in the lateral direction along the concave side of the plate for different longitudinal positions s/s. The measured data are processed using the procedure discussed previously. Fig. 6 shows the contour plot of the turbulence intensity distribution, where the reference velocity (U* in Eq. 5) is equal to the velocity at 30 mm above the plate surface for each longitudinal position. As shown immediately downstream of the plate leading edge, a laminar boundary layer starts to develop, which is characterized by Tollmien-Schlichting waves. By moving downstream, these initially weak, almost isentropic, waves are amplified and finally degenerate into highly random dissipative waves that mark the onset of the boundary layer transition. This is observed at s/s = 0.17. Further downstream, a region of high turbulence intensity is observed, which has a compact peak core that starts at s/s = 0.45 and ends at s/s = 0.65. The contour plot in Fig. 6 should serve as the zero pressure gradient reference profile for comparison purposes discussed below.

Steady Boundary Layer at Negative Pressure Gradient

The steady flow reference case for negative (favorable) pressure gradient was established by horizontally moving the curved plate closer to the convex wall establishing a cross section ratio of A_y/A_x = 1.39 that resulted in a corresponding acceleration ratio of approximately 1.4 as shown in Fig. 4. This ratio was maintained for the periodic unsteady flow case discussed later. Fig. 7 shows the reference turbulence intensity for the steady flow case at negative pressure gradient. This contour plot gives the following interesting picture, which is characteristic of an accelerated boundary layer flow. Similar to Fig. 6, the negative pressure gradient case also reveals a compact high turbulence intensity core above 13% with the center located at s/s = 0.65, the leading edge at s/s = 0.55 and the trailing edge extended beyond s/s = 0.77. The lateral extension of the core is relatively small and is about 30% of the corresponding zero pressure gradient case. Using the longitudinal extension of this high intensity core as a basis, and comparing with the zero pressure gradient case of Fig. 6, suggests that for steady flow the location of the transition onset has moved downstream by about 10%. The use of high turbulence intensity cores of comparable turbulence level allows a more precise comparison, since the exact location of laminar-turbulent transition is always associated with uncertainty, particularly for thin boundary layers.

Periodic Unsteady Boundary Layer at Zero Pressure Gradient

Periodic unsteady flow is established by five rods of 2 mm diameter that are arranged circumferentially on two parallel rotating disks at 300 rpm (see section 2). Each rod generates two wakes with every revolution of the wake generator, one near and one far wake, each at horizontal distances of 252.9 mm and 556.4 mm, respectively, from the leading edge. The near and far wake passing frequency is 25 Hz which corresponds to a period of T = 40 ms. At each position, 400 phase-locked velocity data were taken and processed to generate the time dependent ensemble-averaged velocity and turbulence intensity distributions. The unsteady pattern of the ensemble-averaged velocity distributions are given in Fig. 8a. As shown in Fig. 8a, at s/s = 0.06, the very thin boundary layer close to the leading edge is affected by the periodic unsteady flow. Further downstream, a continuous deformation of the velocity distribution within the boundary layer is clearly visible. Keeping the streamwise position constant at s/s = 0.22, and changing the lateral position from y = 0.3 mm to 25.0 mm, the evolution of the
velocity is shown in Fig. 8b, where strong deformation occurs in
the boundary layer (\(y = 0.3\) mm) and the fully periodic external
flow is reached at \(y > 4\) mm. In Figs. 8c and 8d, the randomness
that is characteristic in a transitional/turbulent boundary layer is
apparent for streamwise locations \(s/s_{m} = 0.50\) and 0.73. As
expected, these figures reveal that the disturbances generated by the
wakes in the boundary layer propagate at slower rate than the wake
outside the boundary layer. Similar observations were made by

A clear picture of the temporal-spatial velocity distribution in
the vicinity of the wall at \(y = 0.3\) mm is given in Fig. 9. Close to
the leading edge at \(s/s_{m} = 0.07\) the periodic velocity distribution
shown in Fig. 9 is not affected by the presence of a very thin
laminar boundary layer. However, a continuous deceleration and
deformation in the longitudinal direction as a result of the
upcoming of turbulent shear stress is clearly visible. This
deflection leads to generation of turbulent spots propagating with
velocities that range between \(0.34U_{m}\) and \(0.59U_{m}\). The process of
turbulent spot generation within the boundary layer starts at \(s/s_{m} =
0.17\), which can be interpreted as the onset of the boundary layer
transition. The dissipative waves mentioned earlier initiate a strong
mixing process within the boundary layer which leads to a fully
random velocity distribution at \(s/s_{m} = 0.75\) marking the begin of a
fully turbulent boundary layer.

Further details of boundary layer transition and development
are shown in Figs. 10 and 11. Fig. 10 shows the contour plot of the
time-averaged turbulence intensity in longitudinal direction having
a compact high turbulence intensity core of above 13\% with the
center located at \(s/s_{m} = 0.48\). The comparison of this core with the
corresponding steady state case of Fig. 6 shows that the periodic
unsteady flow has caused a shift of transition onset towards the
leading edge. The time-averaged turbulence intensity distribution
shown above serves for global comparison purposes only and does
not include the important unsteady details. The following contour
plots, Fig. 11, show a detailed picture of the transition process.

During one rod passing period, the wake flow, as well as
boundary layer transition and development, undergo a sequence of
different flow states. Since this sequence is periodic, we start with
\(t/t_{i} = 0.25\), Fig. 11b, where the quasi-steady "primary" boundary
layer starts at \(s/s_{m} = 0.20\) and extends to the trailing edge of the
plate. The primary boundary layer has a high turbulence intensity
core located around \(s/s_{m} = 0.5\) and is externally disturbed by a wake
strip originating from the a passing wake. As Fig. 11b reveals, the
tail of this strip travels as an external periodic disturbance over the
primary boundary layer. This strip, whose nature will be discussed
in the following paragraph, has apparently not affected the
transition onset, but it has clearly caused a deformation of the
boundary layer picture. Similar observations were made by Pfeil
et al. (1983) and later by Addison and Hodson (1990a,b). The
comprehensive investigations by Orth (1991, 1992) indicate a
similar boundary layer pattern.

At \(t/t_{i} = 0.49\), shown in Fig. 11c, a wake strip hits the plate
leading edge and forms an isolated core with a turbulence intensity
higher than that of the wake strip itself (see the marked region
close to \(s/s_{m} = 0\)). While convected downstream close to the wall,
the turbulence intensities of this isolated core continuously increase,
resulting in degeneration of that wake portion into a periodic
"secondary" boundary layer with a high turbulence intensity core
(13\%) close to the wall. Fig. 11d.

Figure 8(a-d). Ensemble-averaged velocity at various radial
distances from the concave wall at different longitudinal positions
on the plate at zero pressure gradient.
Figure 9. Ensemble-averaged non-dimensional velocity in the temporal-spatial domain at \( y = 0.3 \) mm for zero pressure gradient.

Figure 10. Time-averaged reference turbulence intensity contour for the unsteady case at zero pressure gradient.

By moving further downstream at \( \frac{Vs}{U_s} = 0.72, 0.96, 0.02 \) (or 1.02), Figs. 11d, 11e, and 11a, the periodic secondary boundary layer coalesces with the primary boundary layer resulting in a strong deformation of the latter and generating a high turbulence intensity core. After the secondary boundary layer portion of this strip is totally penetrated into the primary boundary layer at \( \frac{Vs}{U_s} = 0.25 \), extended becalmed regions are formed behind the wake strip and occur far beyond the corresponding longitudinal location of an undisturbed steady boundary layer. Outside the primary boundary layer, the tail of the wake strip travels as an external periodic disturbance as mentioned previously.

The entire set ensemble-averaged data, from which only a few were discussed above, was utilized to generate the temporal-spatial distribution of the ensemble-averaged turbulence intensity for two different lateral positions \( y = 0.3 \) mm and 4.0 mm. As shown in Figs. 12 and 13, the boundary layer is periodically disturbed by the wakes that cause periodically high turbulence cores and extended becalmed regions characterized by Tollmien-Schlichting waves. These regions are observed between the leading edge and the streamwise position of \( \frac{s/s_o}{Vs} = 0.25 \). The existence of the becalmed...
Figure 12. Ensemble-averaged reference turbulence intensity in the temporal-spatial domain at $y = 0.3$ mm for zero pressure gradient.

Figure 13. Ensemble-averaged reference turbulence intensity in the temporal-spatial domain at $y = 4.0$ mm for zero pressure gradient.

Figure 14. Time-averaged reference turbulence intensity contour for the unsteady case at negative pressure gradient.

Figure 15(a-e). Ensemble-averaged turbulence intensity contour for $\tau/\tau = 0.02, 0.25, 0.49, 0.72, \text{ and } 0.96$ at negative pressure gradient.
regions was suggested by Schubauer and Klebanoff (1955), discussed in detail by Pfeil et al. and thoroughly measured by Orth (1991, 1992). It is also worth noting that the propagation velocities of the leading and trailing edges of the turbulent patches represented by the slopes of the dashed lines in Fig. 14 are distinctly different.

Periodic Unsteady Boundary Layer at Negative Pressure Gradient

For the negative pressure gradient case, the horizontal distances of the near and far wake generation are 230.0 mm and 533.5 mm from the leading edge of the plate respectively. Details of the boundary layer transition and development are shown in Figs. 14-17. Fig. 14 shows a contour plot of the time-averaged turbulence intensity in longitudinal direction having a compact high turbulence intensity core of above 13% with the center located at sk = 0.45. The comparison of this core with the corresponding steady state case, Fig. 7, shows that periodic unsteady flow has caused a shift of the center of the core by almost 20% towards the leading edge. This location is preserved throughout the transition process, as discussed below.

Similar to the zero pressure gradient case, and because of the periodic nature of the transition event, we start with uτ = 0.72, Fig. 15d, where the wake has not hit the plate leading edge yet. The external periodic disturbance has apparently not affected the transition onset, but it clearly has caused a deformation of the boundary layer picture.

At uτ = 0.96, shown in Fig. 15e, the wake strip has already hit the plate leading edge. In the vicinity of the wall while convecting downstream, the turbulence intensities of this strip continuously increase forming an isolated periodic secondary boundary layer transition with a high turbulence intensity core, Fig. 15a. At uτ = 0.25, Fig. 15b, it approaches the primary boundary layer and the process of penetration starts. At this time the two turbulence intensity cores are clearly visible. The penetration process is completed at uτ = 0.72.

Similar to the zero pressure gradient case, the entire set of ensemble-averaged data, from which only a few were discussed above, were utilized to generate the temporal-spatial distribution of the ensemble-averaged turbulence intensity for two different lateral positions y = 0.3 mm and 4.0 mm. As shown in Figs. 16 and 17, the boundary layer is periodically disturbed by the wakes that cause periodically high turbulence intensity cores and extended becalmed regions characterized by Tollmien-Schlichting waves. These regions are observed between the leading edge and the streamwise position of sk = 0.23. The existence of the becalmed regions as discussed in the previous case is also clearly visible. However, it should be noted that these becalmed regions are much narrower than in zero pressure gradient case. Two different mechanisms are responsible for this phenomenon. First, the existence of a negative pressure gradient promotes the turbulent mixing, resulting in faster growth of the wake width. This is in full accord with the recent results obtained by Schobeiri and his co-workers (1993). Second, the far wakes are mixed earlier with the near wakes intensifying the mixing effects mentioned above.

Effect of Concave Curvature On Boundary Layer Transition

The effect of surface curvature on the stability of the laminar boundary layer was first investigated by Göttler (1940) and later by Liepmann (1945). For low turbulence intensity (Tu = 0.06%), Liepmann found that the transition may occur if the Göttler number Gb ≥ 7. Mayle (1991) compiled the experimental data of Liepmann and Riley et al. (1989) for higher turbulence intensity levels and created a graph that allows the estimation of the transition range for surfaces with concave curvature. Considering Mayle's graph and the calculation of the Göttler number for the present concave surface boundary layer indicate that the transition by Göttler vortices would occur at sk = 0.5, which is at the location of the high turbulence intensity core, as shown in Fig. 6.

The stability of laminar flow within curved channels under negative pressure gradient investigated by Schobeiri (1976, 1980, 1990), show that on a concave wall, stable laminar flow can be maintained for Reynolds numbers up to 5000. Considering these results, it is assumed that the presence of the negative pressure gradient counteracts the generation of the Göttler vortices.
CONCLUSIONS

The effects of periodic unsteady wake flow and pressure gradient on the boundary layer transition and development along the concave surface of a constant curvature plate were experimentally investigated. The measurements were carried out under zero and negative pressure gradients utilizing an unsteady flow research facility with a rotating cascade of rods positioned upstream of the curved plate. Boundary layer measurements with hot-wire probes were analyzed using the ensemble-averaging technique. Based on the comprehensive experimental investigations partially reported in this paper, the following conclusions are drawn.

1.) The wake induced unsteady flow significantly affects the boundary layer transition behavior leading to the formation of a primary boundary layer with quasi-steady character and a periodic unsteady secondary boundary layer generated by the interaction of wake strips and the wall.

2.) The onset of the primary boundary layer and the location of its high turbulence intensity core is shifted towards the plate leading edge when subjected to periodic unsteady wakes. This shift is probably due to the increased turbulence intensity of the freestream which is caused by intensive the mixing of the incoming wakes.

3.) The secondary boundary layer periodically disturbs the laminar boundary layer leading to periodic transition. It convects towards the primary boundary layer and leaves behind a becalmed quasi-laminar region.

4.) The effect of negative pressure gradient is significant to both steady and unsteady transition. For steady flow, the presence of negative pressure gradient shifted the onset of the high turbulence intensity core and thus the onset of transition downstream by about 10%. For unsteady periodic wake flow, the comparison of this core with the corresponding steady state case shows that periodic unsteady flow has caused a shift of the center of the core by almost 20% towards the leading edge.

DEDICATION

The principal author would like to dedicate this paper to Prof. Dr.-Ing. Horst Pfeil, with whom he had a very fruitful cooperation at the Technische Hochschule Darmstadt (T.H.D) for more than ten years. Prof. Pfeil, who initiated the unsteady transition research program at the T.H.D. in the late sixties, significantly contributed to better understanding of complex transition phenomena. He consistently showed great interest in this research. Two years ago, Prof. Pfeil unfortunately died due to serious illness.

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REFERENCES


