An Experimental Study of Compressible Concave Corner Flows

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Abstract

A naturally developed turbulent boundary layer past concave corners was studied. This investigation is related to the characteristics of the lower surface of a deflected control flap near the cruise speed. The mean surface pressure in Mach 0.64 and 0.83 indicated strong inviscid-viscous interactions. Interaction region increased with the Mach number and the concave-corner angle. The present data supported the validity of the similarity parameter $M_{\infty}\alpha$ as a scaling parameter for the characteristics of the compressible concave-corner flows. The analysis of surface pressure fluctuations indicated that the presence of the concave corner had a minor effect on the unsteadiness of the flows.

List of symbols

$C_p$ pressure coefficient, $(p_w-p_\infty)/q_\infty$
$C_{\sigma_p}$ pressure fluctuation coefficient, $(\sigma_p-\sigma_{p,\infty})/q_\infty$

$M_{\infty}$ Mach number
$p$ pressure
$q_\infty$ dynamic pressure
$U_\infty$ freestream velocity
$x$ coordinate along the surface of the corner
$x_u^*$ Upstream influence region, $x_u/\delta_o$
$x_d^*$ Downstream influence region, $x_d/\delta_o$
$x^*$ $x/\delta_o$
$\alpha$ concave-corner angle in degree
$\eta$ convex-corner angle in degree
$\delta_o$ incoming boundary layer thickness
$\sigma_p$ pressure fluctuation

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Introduction

Improvement of aircraft performance is always one of the major goals for the aerodynamists. Bolonki and Gilyard indicated\(^1\) that deflected control surfaces could be used in combination to provide variable camber control within the operational flight envelopes. The active modification of the control surfaces could potentially play a role in performance optimization for an aircraft, and benefits of variable camber using a simple trailing-edge control surface system can approach more than 10 percent. At the transonic speeds, it is known that increasing camber at the trailing edge can result in maximizing lift-to-drag ratio and higher buffet boundary.\(^2\) However, the critical Mach number, onset of boundary layer separation and drag are also strongly related to the allowable deflection of the control surfaces. Particularly, the boundary layer near the trailing edge of a conventional highly loaded transonic airfoil is considerably weakened due to the steep pressure gradient. Small deflection of the control surfaces may evoke separation.\(^3\) A great deal of uncertainty exists regarding the allowable deflection before separation near the hinge line. A simplified model of the upper deflected control surface (or convex corner flows) was studied by Chung.\(^4\) For the subsonic expansion flows, presence of the convex corner in a turbulent boundary layer results in strong upstream expansion and downstream recompression. The interaction region depends on \(M_\infty\) and \(\eta\). The transonic expansion flows result in milder initial recompression downstream of the corner, and the supersonic region may extend throughout the measurement location at higher \(M_\infty^2\eta\).\(^4\) The boundary layer is separated at \(M_\infty^2\eta \geq 8.95\). Separation position moves slightly upstream and reattachment position moves downstream with increasing convex corner angle, in which the separation length increases with increasing \(\eta\). The measurements of surface pressure fluctuations indicate the intermittent nature of the pressure signals for the transonic expansion flows. The unsteadiness of the flows is related to the type of expansion flow and the shock wave oscillation. The amplitude of peak pressure fluctuations could also be scaled with \(M_\infty^2\eta\).

To further characterize the aerodynamic performance of the deflected control surfaces, the study of the lower deflected control surface is required. The present study examines a turbulent boundary layer past concave corners at high subsonic Mach numbers, Fig. 1. The investigation involves the high subsonic flows past small to larger concave-corner angles. Measurements of surface pressure fluctuation are conducted to study the interaction region and the unsteadiness of the flows. Before discussing the results of present study, brief details of the experiment are outlined next.

Experiment

Transonic wind tunnel

ASTRC/NCKU transonic wind tunnel is a blowdown type.\(^5\) The operating Mach number
ranges from 0.2 to 1.4, and the simulated Reynolds number is up to 20 million per meter. Major components of the facility include compressors, air dryers, cooling water system, storage tanks and the tunnel. The dew point of high-pressure air through the dryers is maintained at -40°C under normal operation conditions. Air storage volume for the three storage tanks is up to 180 m³ at 5.15 MPa. The test section is 600 mm square and 1500 mm long. In the present study, the test section is assembled with solid sidewalls and perforated top/bottom walls. The freestream Mach numbers ($M_\infty$) are 0.63 and 0.82±0.01. In addition, the stagnation pressure ($p_o$) and temperature ($T_o$) are 172±0.5 kPa and room temperature for all the tests.

For the data acquisition system, the NEFF Instruments System 620 and the LeCroy waveform recorders are available. The test conditions are recorded by the NEFF system while the LeCroy 6810 waveform recorders are used for the surface pressure measurements. A host computer with CATALYST software controls the setup of LeCroy waveform recorders through a LeCroy 8901A interface. All input channels are triggered simultaneously by using an input channel as the trigger source.

**Test model**

The test model consists of a flat plate and an interchangeable instrumentation plate. The test model is 150 mm wide and 600 mm long, which is supported by a single sting mounted on the bottom wall of the test section. The concave corner, with 0, 3, 5, 7, 10, and 15-deg angle ($\alpha$), is located at 500 mm from the leading edge of the flat plate. One row of 19 pressure taps for the installation of flush-mounted pressure transducers, 6 mm apart and 2.5 mm in diameter, is drilled perpendicularly to the test surface along the centerline of each instrumentation plate. The side fences at both sides of the instrumentation plate are used to prevent cross flow.

**Experimental techniques**

For the surface pressure measurements, the Kulite (Model XCS-093-25A, B screen) pressure transducers powered by a TES Model 6102 power supply at 15.0 V are used. The outside diameter is 2.36 mm, and the sensing element is 0.97 mm in diameter. The natural frequency is 200 kHz as quoted by the manufacturer. All the pressure transducers are flush-mounted and potted using silicone rubber sealant. Flushness of the pressure transducers is checked by a machinist's block to minimize the interference with the flow. External amplifiers (Ecreon Model E713) are used to improve the signal-to-noise ratio.

Further, the typical sampling period in the present study is 5μs (200 kHz). Each data record possesses 131,072 data points for statistical analysis. The data are divided into 32 blocks. The mean and fluctuating values of each block (4,096 data points) are calculated. Variations of the blocks are estimated to be 0.62 and 0.15 percent for the mean surface pressure coefficient ($C_p$) and the fluctuating pressure coefficient ($C_{\sigma_p}$), which are considered to be the uncertainty of experimental data. For the characteristics of the incoming boundary layer, the normalized velocity profiles for the undisturbed boundary layer at 25 mm upstream of the concave corner appear to be full ($n \approx 7-11$ for
the velocity power law). Moreover, the study by Miau et al.\(^6\) showed that the transition of the boundary layer under the present test condition is close to the leading edge of the flat plate. This indicates turbulent flow at the measurement locations. The boundary layer thickness is estimated to be 7.3 and 7.1±0.2 mm, and the Reynolds number (\(\text{Re}_{\delta_c}\)) is 14.9 and 16.8 \(\times 10^4\) for \(M_\infty = 0.63\) and 0.82 respectively.

**Result and discussion**

**Pressure measurements**

The distributions of mean surface pressure coefficient \(C_p\) along the centerline of the instrumentation plates are plotted in Figs. 2 and 3. The origin of the x coordinate is set at the corner. The distributions appear similar in shape for all the test cases. The flows decelerate upstream of the convex corner, which could be due to the effect of displacement thickness on the effective local wall surface. The implies that the boundary layer thickness upstream of the corner increases, in which larger upstream influence regions are associated with larger concave-corner angles. Moreover, the peak pressures are observed immediately downstream of the corner followed by the expansion. Stronger upstream compression and steeper downstream expansion are associated with the increasing concave-corner angle. At further downstream locations, the level of \(C_p\) tends to an equilibrium value and increases with larger concave-corner angle. The downstream influence region appears to depend on the freestream Mach number and the concave-corner angle. Furthermore, the measurements of surface pressure fluctuation are also analyzed. The characteristics of surface pressure fluctuation, which is determined by a volume integral over the whole boundary layer region, are essentially required for the modeling of sound generation and flow-induced vibration of aerodynamic devices. In Figs. 4 and 5, the surface pressure fluctuation coefficient \(C_{\sigma_p}\) represents the increase of surface pressure fluctuation with respect to the freestream condition. At \(M_\infty = 0.63\), it can be seen that \(C_{\sigma_p}\) decrease slightly within the measurement locations. The presence of the concave corner has a minor influence on the amplitude of surface pressure fluctuations. At \(M_\infty = 0.82\), the damping of surface pressure fluctuations is more significant with increasing concave-corner angle. At further downstream locations, the amplitude of surface pressure fluctuations approaches the undisturbed value, e.g., \(C_{\sigma_p} \approx 0\). This indicates that the influence of a concave corner is minimized on the unsteadiness of the flow.

**Influence of the concave corner**

The objective of the present study is to understand the effect of Mach number and concave-corner angle on characteristics of the compressible concave-corner flows, e.g., interaction regions (upstream and downstream influence) and characteristics of pressure distributions. From the surface pressure distributions, the upstream influence \(x_u\), which is associated with the upstream propagation
of disturbance, can be determined as the intercept of the tangent to the maximum pressure gradient with the upstream surface pressure $p_\infty$ (or $C_p = 0$). Moreover, the downstream influence $x_d$ is estimated from the corner to the intersection of the tangent through the downstream pressure data with the approximately equilibrium downstream pressure. Since the adequate equilibrium downstream pressure can only be approximately obtained, the estimation of the downstream influence region is subjected to more uncertainty, which may be up to $0.3 \delta_o$ at $\alpha = 15$-deg. Furthermore, the extent of the interaction $\xi$ with the presence of a concave corner is then obtained in terms of the upstream and downstream influence regions ($\xi = x_u + x_d$). The upstream influence, downstream influence, and the extent of interaction are plotted in Figs. 6-8. It appears that the concave-corner angle is the major parameter characterizing the upstream influence, which also increases slightly at higher Mach number. Further, the inviscid similarity parameters ($M_\infty^2 \alpha$ or $M_\infty \alpha$) and a similar combined similarity parameter ($\sqrt{1-M_\infty^2} \alpha$) were examined for scaling the upstream influence. However, the parameters ($M_\infty^2 \alpha$ and $\sqrt{1-M_\infty^2} \alpha$) were found to be not applicable for the present test conditions. On the other hand the parameter $M_\infty \alpha$ appears to be suitable. In Fig. 6, the normalized upstream influence appears to be a second order function of $M_\infty \alpha$. For the downstream influence, it increases significantly with the concave-corner angle, particularly at $M_\infty \approx 0.82$. The correlation of the normalized downstream influence and $M_\infty \alpha$ is reasonably well, Fig. 7. The extent of the interaction in Fig. 8 shows a similar trend as those of upstream and downstream influence. It represents the good collapse of the data with $M_\infty \alpha$. A study by Chung indicated that the characteristics of compressible convex-corner flows could be scaled with $M_{\infty}^2 \eta$. This indicates that Mach number effect is more significant for the compressible convex-corner flow than for the compressible concave-corner flows.

Further, the mean surface pressure distributions can be used to estimate the aerodynamic characteristics of the test model. The peak pressure immediately downstream of the corner, and the upstream and downstream pressure gradient characterize the strength of the upstream compression and downstream expansion processes. In Fig. 9 and 10, the present data show that the larger the Mach number and concave-corner angle, the stronger the upstream compression. The peak pressure and upstream pressure gradient can be scaled with a second-order function of $M_\infty \alpha$. For the downstream expansion process, the estimated equilibrium downstream pressures, Fig. 11, can also be scaled with $M_\infty \alpha$. However, it can be seen that the downstream pressure gradient (Fig. 12) is mainly dependent on the concave-corner angle, and the scatter of the data is more evident. As mentioned above, this corresponds to the larger uncertainty for the estimation of equilibrium downstream pressure and the downstream influence scale.

**Conclusions**

Experiments were carried out to study the characteristics of compressible concave-corner flows. The surface pressure distributions show similar characteristics for all the test cases. The
flows decelerate upstream of the corner and accelerate downstream of the corner. Stronger upstream compression and downstream expansion are observed with increasing Mach number and concave-corner angle, which also induce a larger interaction region. A slight damping of surface pressure fluctuations is also observed with the presence of a concave corner. This indicates a minor influence of a concave corner on the unsteadiness of the flow. The similarity parameter \( M_\infty \alpha \) appears to be a suitable scaling parameter to characterize the compressible concave-corner flows. The extent of the interaction region (normalized upstream and downstream influence), peak pressure, equilibrium downstream pressure, upstream pressure gradient, and downstream pressure gradient appear to be the second order functions of \( M_\infty \alpha \) for the present test conditions. In comparison with the compressible convex-corner flows, the Mach number effect is less significant.

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References

Figure 1 Test Configuration

Figure 2 Static pressure distributions, $M_h = 0.63$

Figure 3 Static pressure distributions, $M_h = 0.82$

Figure 4 Pressure fluctuation distributions, $M_h = 0.63$

Figure 5 Pressure fluctuation distributions, $M_h = 0.82$

Figure 6 Upstream influence region