Combined, these results suggest that phase-coupled injection can be used to achieve significantly increased dispersion for all but the largest Stokes numbers where particle trajectories are relatively insensitive to the surrounding carrier phase.

Acknowledgments

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Transition Correlation in Flow over a Swept Cylinder

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Introduction

THE transition process in boundary-layer flow over a highly swept cylinder is dominated by the crossflow instability. It is of practical interest to have an analytical correlation of transition location in low-speed flow over a swept cylinder with parameters such as freestream Reynolds number and sweep angle. In this work, we develop such an analytical correlation, based on the extensive experimental data of Poll.[1]

Analytical Correlation

The experiment of Poll was performed on a faired cylinder with a chord length of $c^* = 457$ mm, which is equal to 4 times the radius R^* ($c^* = 4R^*$); therefore, $R^* = 114$ mm. The experiment was performed at low speed, and the freestream Reynolds number Re varied from 0.22×10^6 to 0.42×10^6, where Re is defined as

$$Re = \frac{Q_\infty^* R^*}{\upsilon^*}$$

Q_∞^* is the dimensional freestream total velocity and υ^* is the dimensional kinematic viscosity. With $R^* = 0.114$ m, the unit Reynolds number was varied from 1.93×10^6 to 3.68×10^6/m. The sweep angle Λ was varied from $\Lambda = 53$ to 70.5 deg. The measured transition onset location varied in a range from $\theta_T^* = 40.1$ to 90.3 deg, depending on the unit Reynolds number and the sweep angle. Here, θ_T^* is the angle between the line that connects the center of the cylinder with the attachment line and the line that connects the center of the cylinder with the transition onset location line. At the same Reynolds number, an increase in Λ results in an upstream movement of the transition onset location. Furthermore, at the same Λ, an increase in the Reynolds number also results in an upstream movement of the transition onset location.

The linear stability calculations for incompressible flow over an infinite swept cylinder indicate that the correlating N factors of stationary (zero-frequency) disturbances at the experimental conditions of the 118 data points of Poll[1] vary from 3.9 to 9.4 with a mean value of 7.4. The corresponding correlating N factors of traveling disturbances vary from 11.6 to 15.7 with a mean value of 14.9. Therefore, for the same initial disturbance amplitude, the amplitude of the traveling disturbance is approximately $e^{14.9}/e^{7.4} \approx 1800$ times larger than the amplitude of a stationary disturbance. These values suggest that traveling disturbances cause transition in the experiment of Poll[1]; this result is consistent with the experimental observations of Poll and is further supported by the scatter in the values of the correlating N factors. For example, the normalized standard deviation off the mean of the correlating N factors of stationary disturbances is 0.14, whereas the corresponding value for traveling disturbances is only 0.04. Note that the linear stability calculations account for the effects of body curvature and nonparallelism. The same physical wave is followed in the calculations by fixing its dimensional spanwise wave number and its dimensional frequency. Details of the mathematical formulation and methods of solution are given by Masad and Malik.[2]

We now analytically correlate the value of x_T with the values of Re and Λ, based on the experimental data of Poll.[1] To do so, we assume that x_T varies with Re and Λ in accordance with

$$x_T = \frac{a^2}{\Gamma_1^2 \Gamma_2^2}$$

where

$$\Gamma_1 = a_1 + (10^{-6} Re)^{a_2} \qquad \Gamma_2 = b_1 + \Lambda^{b_2}$$

In these equations, a, a_1, a_2, b_1, and b_2 are constant and the sweep angle Λ is in radians. The above form acknowledges the destabilizing effects of increasing the freestream Reynolds number and sweep angle. To determine the correlation constants, we minimize the sum

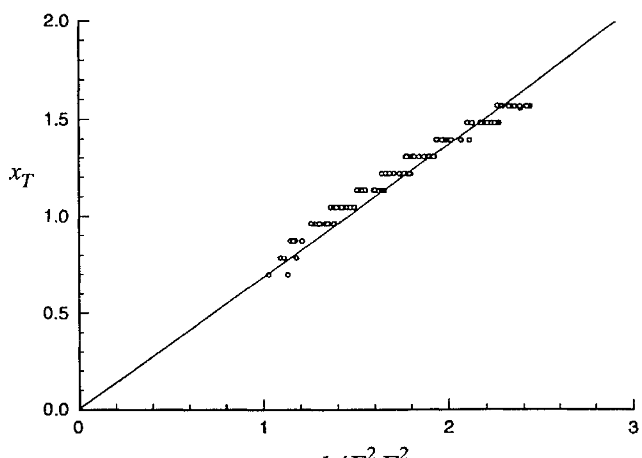

Fig. 1 Comparison between variation of correlated and actual values of transition location with correlation function.

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of the absolute percentage errors. Such minimization results in the following correlation constants:

$$a = 0.83, \quad a_1 = 0.03, \quad a_2 = 0.78$$

$$b_1 = 0.58, \quad b_2 = 1.38$$

The average absolute percentage error that corresponds to these constants is 4.2%. The error bounds on the experimental determination of x_T are ∓ 0.08. A comparison of the variation in the correlated and actual values of x_T with $1/\Gamma_1^2\Gamma_2^2$ is shown in Fig. 1.

Conclusion

The correlation presented here can be used to estimate the transition onset location in low-speed flow over a long swept cylinder for different sweep angles and freestream Reynolds numbers.

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Simulation of Three-Dimensional Symmetric and Asymmetric Instabilities in Attachment-Line Boundary Layers

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Introduction

ON a swept wing, contamination along the leading edge, Tollmien–Schlichting waves, stationary or traveling crossflow vortices, and/or Taylor–Görtler vortices can cause the catastrophic breakdown of laminar to turbulent flow, which leads to increased skin-friction drag for the aircraft. The discussion in this Note will be limited to disturbances that evolve along the attachment line (leading edge of swept wing). If the Reynolds number of the attachment-line boundary layer is greater than some critical value, then the complete wing is inevitably engulfed in turbulent flow. Essentially, there are two critical Reynolds number points that must be considered. The first is for small-amplitude disturbances, and the second is for bypass transition.

Summarized in Table 1, the experimental and theoretical results agree for the critical Reynolds number where small-amplitude disturbances become unstable on the attachment line.[1–4] Accounting for all linear terms, and using an eigenvalue problem approach, Hall et al.[5] studied the linear stability of disturbances in the attachment-line boundary-layer flow called swept Hiemenz flow, which is sketched in Fig. 1. By assuming instability modes that were periodic along the attachment line, the calculations by Hall et al.[5] agreed with the experiments and with the direct numerical simulations (DNS) of Spalart,[6] Theofilis,[7] Jiménez et al.,[8] and Joslin.[9,10]

For large-amplitude disturbances, turbulence decays below some critical Reynolds number and transition to turbulence will occur above this point. At this critical point, termed bypass Reynolds number, transition bypasses the conventional linear instability breakdown process. Summarized in Table 2, the experiments show that disturbances are damped for $R_\theta < 1 \times 10^2$ and the flow becomes turbulent for $R_\theta > 1 \times 10^2$ (Refs. 1 and 11–14).

Hall and Malik[15] attempted to explain this discrepancy between linear theory and the turbulent suppression limits by studying the nonlinear disturbances using weakly nonlinear theory and temporal DNS. Subcritical instability was observed in the computations; however, this subcritical growth did not provide the connection between linear instability and the contamination regions.

Note the wide gap between the linear critical Reynolds number of $R_\theta \simeq 2.45 \times 10^2$ and the turbulent suppression critical Reynolds number of $R_\theta \simeq 1 \times 10^2$. Bridging this gap is important for wing design. The present study will use direct numerical simulations to validate a linear two-dimensional eigenvalue prediction method based on parabolized stability equations by Lin and Malik.[16] This method is considered because it suggests that a number of symmetric and asymmetric modes exist and are stable or unstable on the attachment line depending on the Reynolds number. If validated, the approach would predict a number of modes that are linearly damped in the Reynolds number regime 1×10^2 to 2.45×10^2; however, these modes may grow nonlinearly and provide an explanation to this region.

Table 1 Critical Reynolds numbers for attachment-line instabilities

Experiment	Critical R_θ
Cumpsty and Head[1]	2.45×10^2
Pfenninger and Bacon[2]	2.40×10^2
Poll[3,4]	2.30×10^2
Calculations	2.45×10^2

Table 2 Experimental critical points for attachment-line turbulence suppression

Experiment	Bypass R_θ
Pfenninger[11]	1.0×10^2
Gregory and Love[12]	$9.5–9.8 \times 10^1$
Gaster[13]	$8.8–10.4 \times 10^1$
Cumpsty and Head[1]	1×10^2
Poll[14]	1×10^2

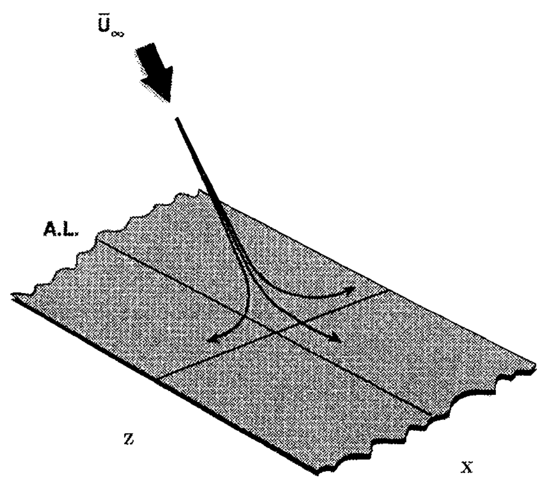

Fig. 1 Sketch of attachment-line region of swept Hiemenz flow.

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