AIAA Journal
Vol. 46, No. 6, June 2008

Technical Notes

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Kelvin–Helmholtz Instability Due to Slot Blowing in Laminar Boundary Layers

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DOI: 10.2514/1.36097

Introduction

BLOWING and suction are widely used to control wall bounded flows. In the case of turbulent boundary layers, the effects of both actuation methods have been thoroughly studied [1–3]. The same applies to the use of suction in laminar boundary layers. In contrast, systematic investigations on the effects of local blowing in initially laminar boundary layers are scarcely found in the literature. Information is especially lacking for studies covering a significant range of blowing rates [4]. In addition, one must bear in mind that laminar boundary layers are very prone to separation via application of concentrated blowing. Further increases of the blowing amplitude have been reported to produce unsteady motion near the dividing streamline. It has been suggested that such event is a consequence of Kelvin–Helmholtz instability [4], but convincing experimental evidence has not been provided. Given the role of unexcited and excited separated shear layers in the context of flow control [5], a survey with the specific aim of characterizing the aforementioned unsteadiness as a function of blowing intensity seems most valuable. The application of low-Reynolds-number boundary-layer control by excitation is envisaged for micro aerial vehicles, which bring new challenges relating to flight aerodynamics.

Both for laminar and turbulent boundary layers in two-dimensional configurations, the effects of suction/blowing have generally been assessed by a measure of the local suction/blowing rate [1–4] as follows:

$$\sigma \equiv \frac{b}{\theta_0}\frac{v_w}{U_\infty} = \alpha\beta \tag{1}$$

where b is the streamwise length of a spanwise slot, θ_0 is the momentum thickness of the undisturbed flow at the slot location, v_w is the suction/blowing velocity, and U_∞ is the freestream velocity. The parameters α and β stand for the corresponding length and velocity ratios, respectively. It must be noted that the quantity defined by Eq. (1) represents a ratio of momentum fluxes associated to blowing/suction ($\rho v_w U_\infty b$) and to the incoming flow ($\rho U_\infty^2 \theta_0$) for an incompressible fluid. However, if extensive boundary-layer separation occurs due to blowing, it seems more appropriate to consider the momentum flux associated with a deflected jet instead [6], thus yielding an additional parameter:

$$\gamma \equiv \frac{b}{\theta_0}\frac{v_w^2}{U_\infty^2} = \alpha\beta^2 \tag{2}$$

Hence, the separated shear layer characteristics, namely those controlling the natural frequency of oscillation f, are expected to be a function of θ_0 and β^2, as given by the corresponding Strouhal number:

$$Sr_n \equiv \frac{f\theta}{\bar{U}} = \frac{2f\theta_0(1+\varepsilon\beta^2)}{U_\infty(1+\beta)} = Sr_{\theta_0}\frac{1+\varepsilon\beta^2}{1+\beta} \tag{3}$$

where $\bar{U}$ is the mean velocity for the mixing streams and ε is an unknown factor to account for the modification of the momentum thickness at separation θ_0 as a result of slot blowing at a value of momentum flux ratio β^2.

The main purpose of the present study is to provide experimental substantiation of the idea that the unsteady regime identified as "vortex shedding" in [4] for the higher values of σ is indeed associated to the presence of classical, separated shear layer instability. A description of how the nondimensional roll-up frequency $Sr_{\theta_0} \equiv 2f\theta_0/U_\infty$ depends on blowing parameters has been proposed and it is experimentally evaluated. In addition, a comment is made with respect to the discrepancies which may occur when comparing experiments and numerical simulations of slot blowing.

Flow Conditions and Experimental Procedure

The experimental setup is schematically illustrated in Fig. 1. A laminar boundary layer with approximately constant freestream velocity U_∞, exhibiting a momentum thickness θ_0 at $x = 0$, is formed on the bottom wall of the test section in a wind tunnel. The flow upstream is ducted through a large plenum chamber containing four honeycombs and grids, which are followed by a 20:1 smooth contraction [7]. Basic dimensions of the test section are a length $L > 750\theta_0$, a height $h > 125\theta_0$, and a width $w > 625\theta_0$, along the streamwise, wall-normal, and spanwise directions, respectively. Slot blowing is applied at the wall in the y direction, characterized by a constant average bulk velocity v_w. An independent air supply feeds the slot of width w and thickness b, following a plenum chamber containing various settling elements and a linear 10:1 contraction [7].

Two different Reynolds numbers Re_{θ_0} have been considered in the present investigations for six blowing rates covering a significant range of values. The flow conditions, including the shape factor H characterizing the boundary-layer profile at $x = 0$, are summarized in Table 1. Upstream of the slot, the values of freestream turbulence intensity ($Tu = 0.3\%$) and longitudinal pressure gradient remained nearly unchanged during the tests. The laminar boundary layers were subjected to a mildly favorable pressure gradient, corresponding to a Thwaites' pressure gradient parameter $\lambda = 0.01$. Using these data, Granville's method predicts that an increase in Reynolds number $\Delta Re_\theta \approx 800$ is required after the initial amplification of small disturbances for laminar-to-turbulent transition to occur. In addition, linear stability theory indicates that the boundary-layer profiles at

Received 7 December 2007; revision received 15 March 2008; accepted for publication 16 March 2008.

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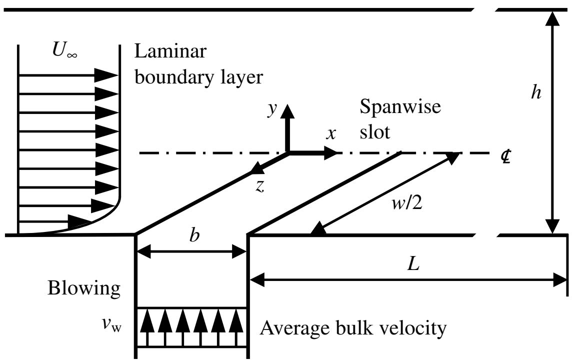


Fig. 1 Schematics of experimental setup.

Fig. 2 Flow visualization for $Re_{\theta_0} = 107$: a) $\sigma = 1.9$, b) $\sigma = 3.8$, c) $\sigma = 7.6$.

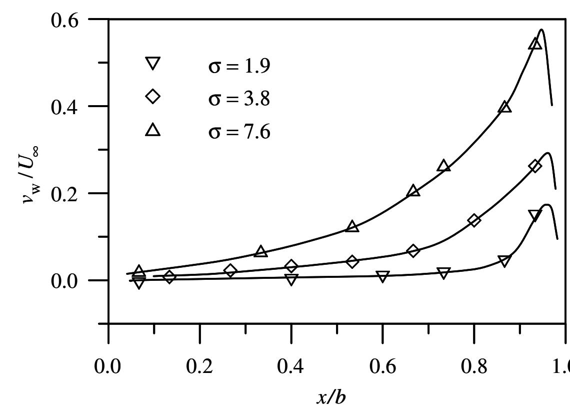


Fig. 3 Wall-normal velocity distribution along thickness of slot for various blowing rates.

$x = 0$ are very stable to small disturbances. An early appearance of transition and spanwise nonuniformities by transverse contamination [8] at this location was also ruled out by surveying the longitudinal velocity profiles at a width of $0.4w$ around the measurement plane. Finally, owing to the very large value of the ratio w/θ_0, the initial stages of the flow downstream of the slot are expected to be mostly free of parasitizing three-dimensional effects.

Nonintrusive velocity measurements have been performed at the plane $z = 0$ only, employing a laser Doppler velocimetry operated in dual-beam, back-scatter mode (Dantec, Denmark). Velocity statistics were calculated by ensemble averaging, typically from 10,000 samples, thus leading to statistical errors below 1% for mean values. The velocity time series taken near the dividing streamline were used in the spectral analysis of the flow, fulfilling the requirements mentioned in [9]. Argon-ion laser illumination and paraffin oil particles have been used as light source and tracers, respectively, both for velocity measurements and visualization of the unsteady flow pattern in the vicinity of the wall. A system of oscillating mirrors was employed to form a vertical light sheet at the midspan of the test section as well as to obtain stroboscopic effects, which facilitated the identification of time-periodic flow structures. Snapshots were recorded at a right angle to the sheet of light using a $1/3''$ charge-coupled device (CCD) digital camera.

Results and Discussion

Similar patterns have been obtained by flow visualization for corresponding values of σ, irrespective of the Reynolds number. A mere decrease in flow organization was observed for the highest value of Re_{θ_0}. Consequently, only flow visualization results for $Re_{\theta_0} = 107$ are presented here. The effect of the blowing rate on the flow near the dividing streamline can be appreciated in Fig. 2, which shows representative snapshots. It can be seen that the smaller the blowing rate, the sooner the roll up of the separated shear layer occurs. The flow structures are remarkably coherent at $\sigma = 1.9$ and 3.8, but such organization is impaired with further increases of the blowing rate. Assuming a value of $Sr_n \approx 0.026$ for the nondimensional, natural instability frequency of the separated shear layer [10], a wavelength $l \approx 38\theta_0$ is expected for the Kelvin–Helmholtz roll up. In fact, it can be seen from the flow visualization images that the foregoing condition was verified for the lower value of σ, noting that we have also set $\alpha \equiv b/\theta_0 = 38$ in the experiments for $Re_{\theta_0} = 107$. According to the literature, steady motion was

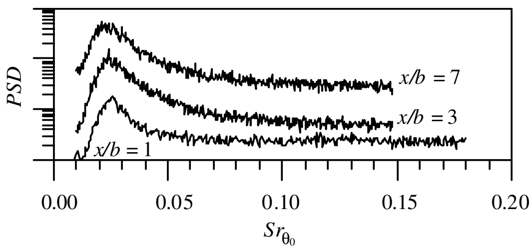
Table 1 Flow conditions

Re_{θ_0}	H	α	β	σ	γ
			0.05	1.9	0.10
107	2.1	38	0.1	3.8	0.38
			0.2	7.6	1.5
			0.05	2.8	0.14
142	2.0	55	0.1	5.5	0.55
			0.2	11.0	2.2

expected for this flow condition [4]. However, a reason for the discrepancy may be found by comparing the blowing velocity profiles at the exit of the slot in the present experimental investigation with those prescribed in the aforementioned numerical study. Figure 3 shows the measured wall-normal velocity distribution along the thickness of the slot, for various blowing rates. The results demonstrate that the slot blowing velocity profile is far from uniform, which is the usual boundary condition in related numerical studies [2,4]. The locally, much larger, velocities in the vicinity of the downstream edge of the slot lead to a sudden deflection of the incoming boundary layer at this location. Such effect, being more pronounced for low σ, is likely to be responsible for the earlier onset of flow unsteadiness in the experiments.

The good agreement of the shedding frequency observed in two-dimensional laminar boundary-layer separation, due to a suddenly imposed adverse pressure gradient with the most amplified linear inviscid instability of the separated shear layer, was noted before in numerical simulations [11]. When separation is produced by the application of slot blowing instead, one may expect such agreement to hold throughout the range of blowing intensities as long as proper account is taken of its effects on the basic characteristics of the separated shear layer. To investigate this matter, velocity power spectra of the wall-normal velocity component have been obtained along this layer, near the y location where the peak fluctuations occur. Representative results are shown in Fig. 4 for different streamwise stations and all flow conditions.

It must be mentioned that an arbitrary scale has been used for the power spectral density (PSD), so that the data have been occasionally shifted for the sake of clearness. As expected, humps were found in the measured power spectra, revealing the natural roll up of the shear layer, which is a broadband process due to naturally occurring jitter. In accordance to the findings of the flow visualization study, the value of Sr_{θ_0}, corresponding to the dominant frequency for the smaller blowing rate, is close to 0.026. Although this frequency exhibited a clear decreasing trend as the blowing rate was increased,



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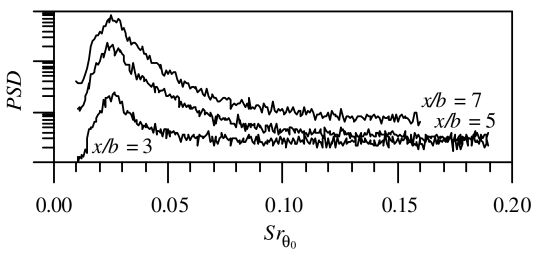

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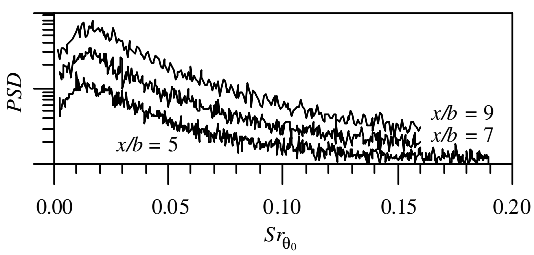

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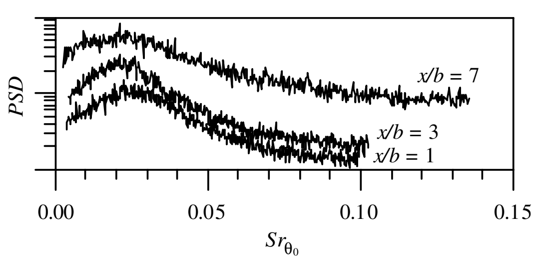

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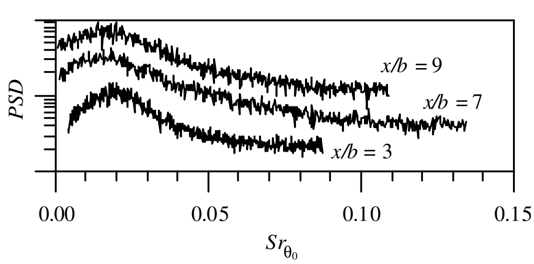

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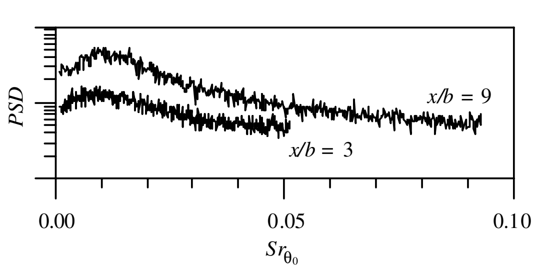

f)

Fig. 4 Velocity power spectra along separated shear layer: a) $Re_{\theta_0} = 107$, $\sigma = 1.9$, $y/\theta = 5, 8, 8$; b) $Re_{\theta_0} = 107$, $\sigma = 3.8$, $y/\theta = 8, 13, 13$; c) $Re_{\theta_0} = 107$, $\sigma = 7.6$, $y/\theta = 18, 23, 23$; d) $Re_{\theta_0} = 142$, $\sigma = 2.8$, $y/\theta = 11, 19, 26$; e) $Re_{\theta_0} = 142$, $\sigma = 5.5$, $y/\theta = 26, 33, 33$; f) $Re_{\theta_0} = 142$, $\sigma = 11.0$, $y/\theta = 45, 56$.

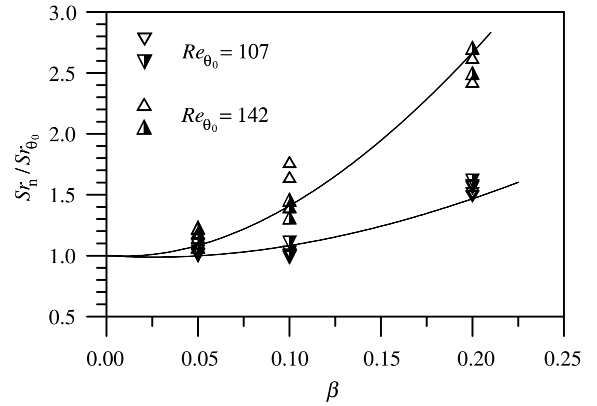

Fig. 5 Effect of blowing rate on nondimensional instability frequency.

it remained nearly unchanged as the separated shear layer evolved downstream. This is a confirmation that three-dimensional effects did not play a significant role in the phenomenon at this stage. As the frequency peak associated with natural instability broadens considerably with the increase of both blowing rate and Reynolds number, a procedure was devised to cope with the growing uncertainty. Thus, two frequency values have been extracted from each measurement, one corresponding to the maximum of the spectral line and the other to the mean value of the frequency range defined by the full-width at half-maximum (FWHM) of the spectral line. The former values were discarded when the difference to the latter was too large. These data were plotted in Fig. 5 in the form of a ratio Sr_n/Sr_{θ_0} as a function of parameter β, where open and half-closed symbols represent the frequencies defined by the maximum in PSD and the mean of the FWHM, respectively. Good agreement with the functional square dependency on β, expressed by Eq. (3), is obtained (solid lines in Fig. 5), empirically taking $\varepsilon \approx \alpha$ and $\alpha/2$ for $Re_{\theta_0} = 142$ and 107, respectively. It is interesting to point out that a decrease in Strouhal number with blowing has also been reported to occur in the case of the flow around a cylinder (von Kármán vortex shedding) [12]. Despite the differences in flow topology, the underlying mechanism is thought to be the same in both cases, i.e., the manipulation of the separated shear layer characteristics by blowing.

Conclusions

An experimental investigation of a laminar boundary layer subjected to blowing from a spanwise slot has been carried out for a significant range of blowing rates and two different Reynolds numbers. It was demonstrated that the flow unsteadiness previously described in related numerical studies is associated to classical, shear layer instability. Flow visualization and velocity power spectra measured along the dividing streamline have allowed the effect of blowing on instability frequencies to be analyzed. It was concluded that, similarly to the case of von Kármán vortex shedding, blowing leads to a decrease in Strouhal number. A physically based functional to describe this effect as a function of blowing rate has been proposed and verified. Additional experiments are desirable to clarify the dependence on the Reynolds number.

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