Instability of streamwise vortices over a curved wall.

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Abstract

Curved streamlines generated by Görtler mechanism produce steady vortical structure, known as Görtler vortices. The nonlinear evolution of that vortices was experimentally investigated on a concave-convex curved model. Experiment indicated that the linear state can be brief and the nonlinear regime dominates the primary instability. It also revealed that the developed mushroom-like structures are almost observed in that nonlinear stage. Hot-wire measurement of the velocity field allowed reconstruction of the vortex structure. The wall-normal and spanwise profiles of the streamwise component of the velocity showed simple and multiple inflection points. The profiles become more complex as the flow field becomes more nonlinear state. Spectral analysis of the spanwise profiles of the streamwise component show that only some modes suffice to represent the velocity field in the nonlinear regime.

Introduction

Centrifugal instability of wall shear layers, known as Görtler instability (Görtler 1954) produces streamwise vortical structures growth in a laminar boundary layer. Görtler problem has at least tow particular characteristics that make it different from other instabilities. It has, usually, a curt linear regime that the vortices almost appear in the nonlinear regime. Depending on experimental conditions, the mode of the secondary instability, sinuous type or varicose type, depends upon the wavelength initially developed.

Many studies have investigated on the nonlinear evolution of Görtler instability. Most of that work presents a numerical studies, and it had been the subject of a number of investigations (Herbert 1976, Hall 1988, Floryan & Saric 1982, Sabry & Liu 1991, Lee & Liu 1992 and Li & Malik 1995).

The experimental works are less numerous (Bippes & Görtler 1972, Bippes 1978, Swearingen & Blackwelder 1987, Peerhossaini & Wesfreid 1988, Kohama 1987, Peerhossaini & Bahri 1997), making the numerical-experimental comparison difficult. In this investigation we report the results of an experimental studies of Görtler instability in the linear, nonlinear regimes and especially a decomposition by spectral analysis of the nonlinear evolution.

Experimental apparatus

Experiments were run on a concave-convex model fixed in a low-speed wind tunnel with a nominal free stream velocity of 2 m/s. The model, Figure 1, consists essentially of a concave part of 65 cm radius of curvature, followed by a convex one. A flat plate tangent to the convex wall at its summit, which can pivot around the center of curvature of the convex part, completes the working surface of the model. Spanwise wavelength are triggered artificially through a 0.2 mm-diameter wire grid vertically positioned at the leading edge. The wavelength is fixed to 30 mm.

Flow visualizations are performed by injecting smoke through a slit of 0.7 mm thickness inclined at 45°. The boundary layer is enlightened by an Argon laser sheet oriented normally to the wall at different streamwise positions. Görtler vortices are viewed by a camera mounted perpendicularly to the plane of the laser sheet.

Single hot-wire probe is used to measure the streamwise component of the velocity. The probe scans, at each streamwise location, the boundary layer cross-section in wall-normal and spanwise directions.

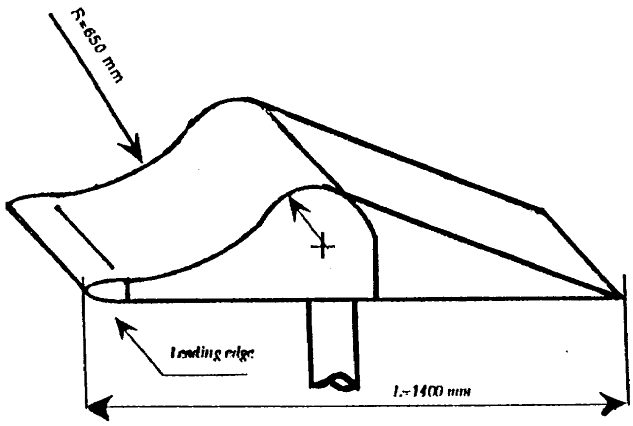


figure 1: Concave-convex model.

Results and discussion

Flow visualizations are performed at four streamwise positions located at x = 95, 260, 425 and 580 mm from the leading edge.

At the first location x = 95 mm from the leading edge smoke visualization don't reveal any significant rotating structure. At x = 260 mm, Figure 2 (a), a local growth "small hump" of smoke has been observed in back of each trigging wire. However, streamwise location x = 425 mm shows three pairs of developed vortices presented in Figure 2 (b).

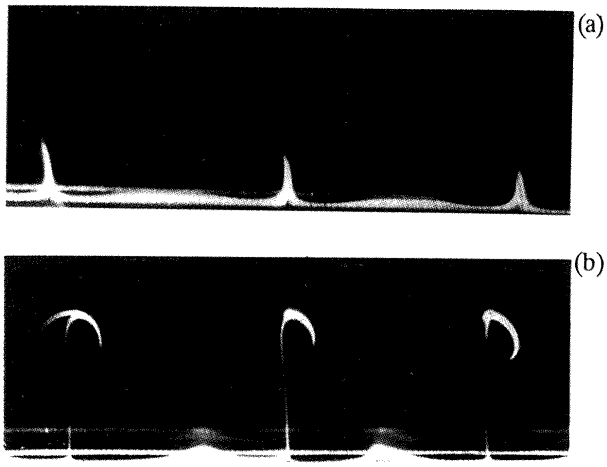


Figure: 2, Visualization of Görtler vortices at a) x=260 , b) 425 mm from the leading edge.

Hot-wire measurements of the streamwise velocity permitted the reconstruction of the vortex structure. Figure 3 (a) shows, at the position x = 95 mm, that the boundary layer is more or less uniform except at its edge where the effects of the disturbed-wires are distinct. At x = 260 mm, Figure 3 (b), the iso-velocity lines present an undulation in the low speed region situated behind each disturbed-wire. That undulations discern the rotation of the streamwise vortices. However, at x = 425 mm figure 3 (c) shows that the boundary layer thickness change its shape, the vortices are fully developed and situated at the edge of the boundary layer.

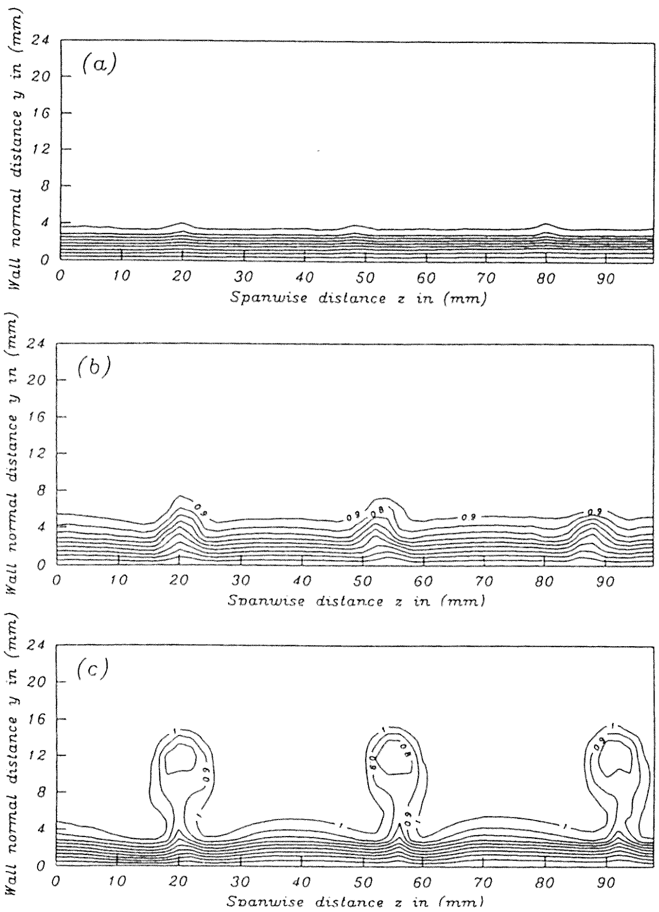


Figure: 3, Iso-velocity lines at the locations: a) x=95 mm, b) x=260 mm and c) x=425 mm.

Figure 4 shows the distribution of the mean streamwise velocity plotted against z/λ of one pair of vortex located at x = 260 mm. It shows that the velocity presents a deficit in the peak region "low speed region" due to the pumping of the fluid particles of low momentum situated near the wall. However, at x=425 given by Figure 5, the streamwise velocity modify completely its distribution over the boundary layer. Therefore, multi-inflexional profiles appear in the peak "region of low speed" and over a layer situated from y=0.6 δ to y=0.8 δ. Away from that layer, the profiles became simple-inflexional and are similar to the pervious location.

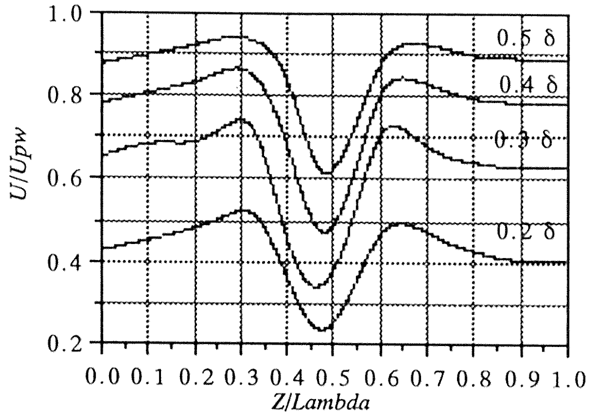


Figure 4: Spanwise distribution of the velocity at x=260 mm.

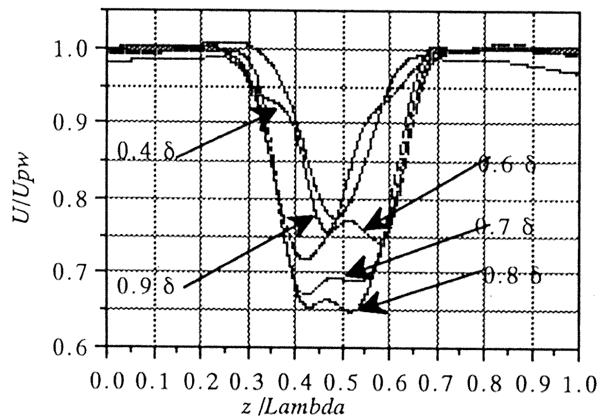


Figure 5: Spanwise distribution of the velocity at x=425 mm.

In order to study the nonlinear regime of Görtler vortices, the streamwise component of the disturbance velocity can be described in terms of Fourier series expansion as:

$$u'(x,y,z) = u_0 + \sum_{n=1}^{N} u_n(x,y)\cos(n\alpha z)$$

where u' is the disturbance velocity, α is the wave number and n represents the truncation number for Fourier series, which should be properly chosen to give an accurate solution. Thus a spectral analysis was performed on the spanwise profiles of the streamwise velocity by an FFT algorithm and the spectral distribution of modes in the nonlinear state of the Görtler vortices was obtained. In Figure 6 are plotted the amplitude of disturbances for different modes. It shows that only six or seven modes can describe satisfactorily the measured velocity field.

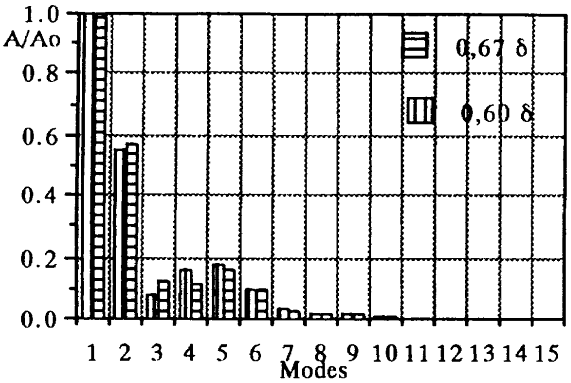
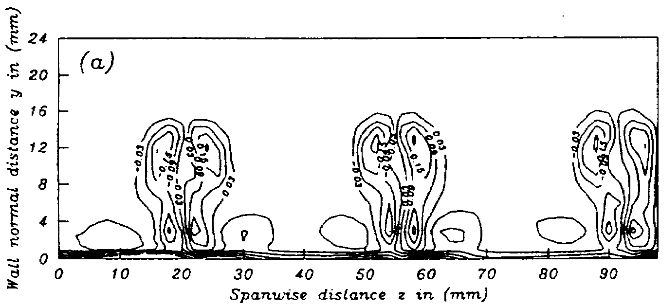


Figure: 6, Power spectrum at x=425 mm

The wall-normal and spanwise iso-shears $\partial U/\partial y$ and $\partial U/\partial z$, calculated from the same data of figure 3, are presented in Figure 7. They show that the iso-shears $\partial U/\partial z$ grow faster than the $\partial U/\partial y$ and the inflexional profiles appear in the spanwise direction earlier that the wall-normal direction.

The secondary instability was not observed due to the model shape. The convex-part of the model accelerate the flow and modify the growth of the streamwise vortices. However, the rapid growth of $\partial U/\partial z$ lets suggested that the sinuous mode of the secondary instability will be appears. This results confirm the work of Swearingen & Blackwelder that the sinuous mode of the secondary instability appears first and it is related to $\partial U/\partial z$.



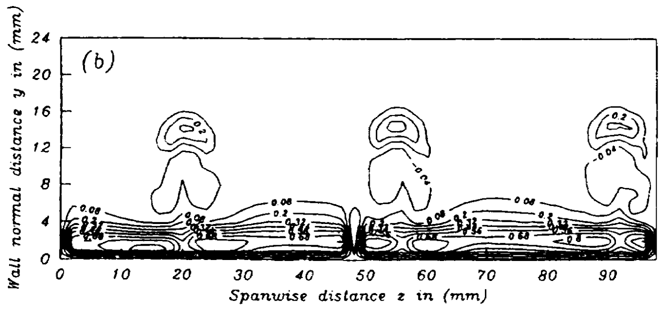


Figure: 7, Iso-shear contours of: (a) $\partial U/\partial z$ and (b) $\partial U/\partial y$ at the location x=425 mm.

Conclusion

The nonlinear evolution of Görtler vortices generated on a concave-convex model was experimentally studied. Flow visualization as well as hot-wire measurements indicated that the linear state can be brief and the nonlinear regime dominates the primary instability.

Hot-wire measurements, scanned in the cross-section of the boundary layer, showed simple and multiple inflection profiles in different streamwise locations.

A spectral analysis was performed on the spanwise profiles of the streamwise velocity using an FFT algorithm, and the spectral distribution of the modes in the nonlinear state was obtained. It was shown that the power spectrum of different modes is non uniformly distributed in the frequency space and only six or seven modes are requested to determine the velocity.

The iso-shear layers show that $\partial U/\partial z$ appears before $\partial U/\partial y$. It is inferred that the sinuous mode of the secondary instability would be the dominant mechanism should this instability occur.

Flow visualization confirmed that the developed mushroom-like structures are almost observed in the nonlinear stage when the inflexional profiles, in the spanwise direction, are formed.

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