Visualizing Görtler Vortices

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Abstract: The development of Görtler vortices with pre-set wavelength of 15 mm has been visualized in the boundary-layer on a concave surface of 2.0 m radius of curvature at a free-stream velocity of 3.0 m/s. The wavelength of vortices was pre-set by vertical wires of 0.2 mm diameter located 10 mm upstream of the concave surface leading edge. The velocity contours in the cross-sectional planes at several streamwise locations show the growth and breakdown of the vortices. Three different regions can be identified based on different growth rate of the vortices. The occurrence of a secondary instability mode is indicated by the formation of a small horseshoe eddies generated between the two neighboring vortices traveling streamwise, to form mushroom-like structures as a consequence of the non-linear growth of the Görtler vortices.

Keywords: Görtler vortices, Pre-set wavelength, Mushroom-like structures, Horseshoe vortices, Boundary layer.

1. Introduction

Görtler vortices (Görtler, 1940) are streamwise counter-rotating vortices that may develop in a laminar boundary layer along concave surface, as sketched in Fig. 1. Such vortices are due to centrifugal instability which causes an imbalance between centrifugal force and radial pressure gradient in boundary-layer flow over a concave surface, and will occur if the Görtler number $G_{θ}$, as defined by (Smith, 1955):

$$G_{θ} = \frac{U_{∞}}{\theta} \sqrt{\frac{\nu}{R}}$$

exceeds a critical value $G_{θc}$, where $\nu$ is the fluid kinematic viscosity, $\theta$ the momentum thickness based on Blasius boundary-layer profile, $U_{∞}$ the free-stream velocity, and $R$ the concave surface radius of curvature. The vortices will be amplified downstream resulting in a three-dimensional boundary-layer due to distribution of streamwise momentum which causes spanwise variation in the boundary-layer thickness, and consequently will form the “upwash” region, where low momentum fluid moves away from the wall, and the “downwash” region, where high speed outer fluid moves towards the wall (Fig. 1). At the “upwash”, the boundary-layer is thicker and the shear stress is lower than those at the “downwash”.

Due to the importance of concave surfaces in many fluid engineering applications, such as turbine blades and aerofoils, the effects of Görtler vortices on boundary layer development, heat transfer and deposition, can not be ignored. The wavelength selection of Görtler vortices is not clearly understood yet.
However, it is known that the onset and development of Görtler vortices are influenced by the initial disturbances, and that the leading edge receptivity influences the resulting vortex wavelengths that appear in the experiments. That is, Görtler instability amplifies the wavelength imposed by the rig on the incoming flow (Kottke, 1988), and a competition of perturbation with different amplification rates, as the only wavelength selection mechanism of Görtler vortices, resulting in non-uniform wavelengths in naturally developing Görtler vortices. Swearingen and Blackwelder (1986) used spectral analysis to determine the vortex wavelength. It gave the same estimation as the average wavelength estimated from the smoke wire visualization of naturally developed Görtler vortices.

By assuming that only vortices with maximum local amplification can appear in the experiments, a simple method based on the Görtler vortex stability diagram (of Smith (1955), for example) can be used to predict the wavelength of Görtler vortices. In this method, the non-dimensional wavelength parameter $\Lambda$ is defined as:

$$\Lambda = \frac{U}{\lambda} \sqrt{\frac{\alpha}{\beta}}$$

where $\lambda$ is the Görtler vortex wavelength receiving maximum amplification and $\Lambda$ represents a family of straight lines which cross the Görtler vortex stability diagram (see Mitsudharmadi et al., 2004, for example). $\alpha$ is called dimensionless wave number and $\alpha = \frac{2\pi}{\lambda}$. Luchini and Bottaro (1998) found that the most amplified wavelengths are for $\Lambda$ ranging from 220 to 270, which agrees with those reported earlier, for example, by Floryan (1991), Smith (1955), and Meksyn (1950) who respectively proposed $\Lambda = 210, 272$, and 227.

Visualizations of Görtler vortices can be classified into three groups: 1) Surface flow visualizations, such as those by Highnett and Gibson (1963), McCormack et al. (1970), and Kemp (1977); 2) Suspended particle flow visualizations, such as those by Kahawita and Meroney (1977), Ito (1987), Swearingen and Blackwelder (1987), Petitjeans et al. (1997), and Ajakh et al. (1999); and 3) Electrolytic flow visualizations, such as those by Wortmann (1969), Bippes and Görtler (1972), and Winoto and Crane (1980).

Since the wavelengths of naturally developed Görtler vortices are not uniform, Perhossaini and Bahri (1998) used a series of 0.2 mm-diameter vertical wires placed upstream to concave surface leading edge to pre-set the spanwise position of Görtler vortices. Using this arrangement, the wavelengths of the resulting Görtler vortices are uniform and equal to the spanwise distance of the vertical wires.

The aim of this work is to study the development of Görtler vortices in the boundary-layer on a concave surface of 2.0 m radius of curvature by means of hot-wire anemometry. For convenience and ease of investigation, uniform wavelength Görtler vortices are used. The vortex structures will then be visualized by plotting the contours of streamwise velocity component.