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Development of streamwise counter-rotating vortices in flat plate boundary layer pre-set by leading edge patterns

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ABSTRACT

Development of streamwise counter-rotating vortices induced by leading edge patterns with different pattern shape is investigated using hot-wire anemometry in the boundary layer of a flat plate. A triangular, sinusoidal and notched patterns with the same pattern wavelength λ of 15 mm and the same pattern amplitude A of 7.5 mm were examined for free-stream velocity of 3 m/s. The results show a good agreement with earlier studies. The inflection point on the velocity profile downstream of the trough of the patterns at the beginning of the vortex formation indicates that the vortices non-linearly propagate downstream. An additional vortex structure was also observed between the troughs of the notched pattern.

1. Introduction

Development of streamwise counter-rotating vortices within the boundary layer is a well-known passive flow control resulting in the momentum exchange between the free-stream flow and the boundary layer flow. Such vortices cause the boundary layer to be re-energized and the transition process to be expedited. The streamwise counter-rotating vortices, generated in either natural or forced manner, can be observed in many engineering applications such as airfoils, turbomachines and heat exchangers. Such streamwise counter-rotating vortices are generally developed as secondary flow in instability problems. Rayleigh [1], Taylor-Couette [2], Dean [3], Görtler [4] instabilities are the well-known examples demonstrating the existence of such streamwise counter-rotating vortices. The wavelengths of the natural counter-rotating vortices are often variable as a result of a competition of perturbation with different amplification rates [5,6]. To examine the vortices in a controlled environment, perturbation devices such as a vortex generator [7], thin wire [5,8] and roughness [9] were used to induced its formation. The leading edge pattern is another approach to pre-set streamwise counter-rotating vortices [10–12]. It is inspired by the observations of humpback whales which are more agile in pursuing their prey compared to the other whales.

The preliminary investigation revealed that the leading edge protrusions of humpback whales flippers are the distinctive feature of this species [13,14]. The leading edge protrusions cause earlier flow separation downstream of the valley between the adjacent protrusions which bring about changes in aerodynamic characteristics of an airfoil [15]. This approach can also increase stall angle or prevent dramatic lift drop at post-stall and raise the maximum lift [16]. However, there is no benefit on the pre-stall condition due to the leading edge protrusions [15,17–19].

The leading edge protrusions are functionally comparable to conventional vortex generators and delta-wings due to the similarity in the development and characteristics of such streamwise counter-rotating vortices within the boundary layer [19,20]. The geometrical features of the leading edge protrusion including the amplitude and wavelength affect the aerodynamic performance of the approach due to changing the vortex structures [15,19,21]. The surface curvature, configuration of the bumpy surface and Reynolds number are the other parameters that affect the effectiveness of the leading edge protrusions [19,21,22].

To have a more insight on the role of leading edge pattern to the evolution of streamwise counter-rotating vortices, the flat plate model with the leading edge pattern were used in the current study. In the previous study of the Görtler instability, the initial occurrence of streamwise counter-rotating vortices is indicated

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Nomenclature

A	amplitude of leading edge patterns (peak to trough)
n	total number of data samples at a given point over the sampling duration
Tu	turbulence intensity level of the flow
u'	fluctuating velocity component in the streamwise direction
u	mean velocity
$\widehat{U}_i$	velocity of a measured sample
U_∞	free-stream velocity
x, y, z	streamwise, normal, spanwise distance

Greek symbols

δ	boundary layer thickness based on Blasius solution
η	dimensionless coordinate normal to the wall ($= y\sqrt{U_\infty/x\upsilon}$)
λ	wavelength of leading edge patterns
ν	fluid kinematic viscosity

by the waviness of the boundary layer thickness along the spanwise direction [5,23–30]. As it evolves downstream, the perturbation is amplified and the waviness shape will transform into the mushroom-like structures. It causes the low momentum fluid to be lifted up from the wall in the "upwash region" where the boundary layer is thicker. The upward movement of the low momentum fluid is indicated by the formation of the stem of the mushroom-like structures. Since this low momentum fluid cannot penetrate the high momentum in the free-stream, it will be deflected down to form the mushroom hat. This causes the entrainment of high momentum fluid from the free-stream into the boundary layer in the downwash region where the boundary layer is thinner. Due to this, the velocity profile in the downwash region is fuller than that in the upwash region.

Unlike the occurrence of the streamwise counter-rotating vortices in the Görtler instability study, it has been reported that the presence of leading edge patterns, regardless the geometrical shape of the pattern, generate streamwise counter-rotating

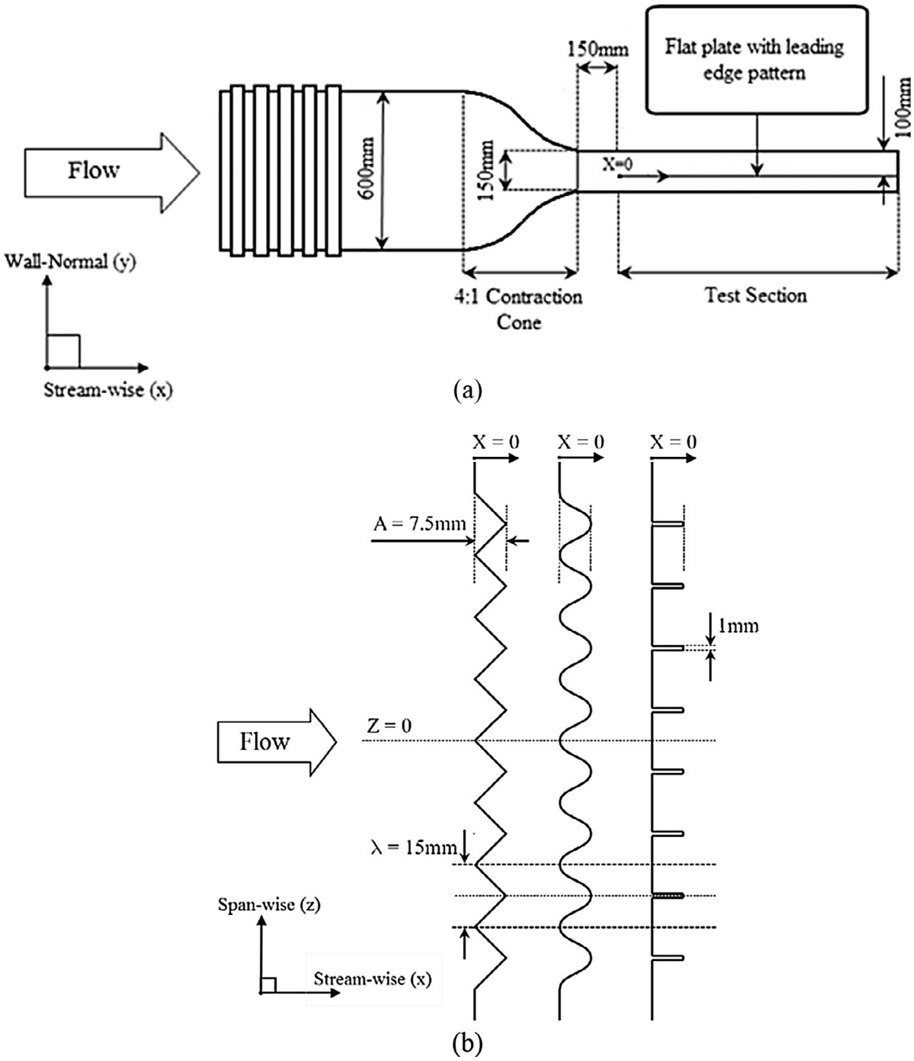

Fig. 1. Schematic of (a) experimental set-up, (b) leading edge patterns (left to right): triangular (T-λ15A7.5), sinusoidal (S-λ15A7.5) and notched patterns (N-λ15A7.5).