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EFFECTS OF REYNOLDS NUMBER ON THE ONSET OF LEADING EDGE VORTEX SEPARATION ABOVE BLUNT-EDGE DELTA WING VFE-2 CONFIGURATIONS

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Abstract

This paper discusses the effects of Reynolds number on the passage of leading-edge vortex separation onset above blunt-edged delta wing VFE-2 configurations. The VFE-2 model differentiated by its leading edge radii namely medium and large-edged wings were fabricated and tested in UTM-Low Speed Wind Tunnel, (UTM-LST). The tests in this study were performed at speeds of 18, 36.1 and 54.2 m/s correspond to Reynolds numbers of 1×10^6*,* 2×10^6 *and* 3×10^6 *based on the mean aerodynamic chord. The correlation between the leading-edge pressure coefficients on the onset of leading edge primary separation is discussed in this paper. The experimental results obtained from surface pressure measurements carried out on the upper surface of the model showed that higher Reynolds number can delay the formation of the primary vortex towards the aft portions of the wing.*

1 Introduction

For sharp-edged delta wing, the flow moves from the lower to the upper surface into a spiral type of motion. Flow separation will take place at the leading edge near the apex. At a certain angle of attack, the *primary vortex* is developed on the upper surface. The primary vortex basically start as small shear layers at the leading edge and then wrap up into a spiral fashion [1].

However, the flow physics on the round-edged delta wing exhibit differences from the sharp-edged wing especially in the region near to the leading edge and the apex. A detailed flow topology above blunt-edged delta wing had been discussed in detail within the VFE-2 campaign [2][3][4]. The main difference between the sharp and blunt profile is the attached flow region occurred in the apex region. In this area, the flow attaches to the wing surface, starting from the apex to a certain chord-wise position which depends on Reynolds number, angle of attack, Mach number and the leading edge profile [2][5][6][7][8]. Further downstream, the flow starts to separate and primary vortex is developed in the leading edge region.

The extension of the attached flow on the blunt-edged wing depends on the angle of attack, Reynolds number, Mach number and the leading-edge bluntness. Surface pressure studies by Chu and Luckring [9] and PIV studies by Konrath *et al* [10] had showed that the primary vortex is initiated at a certain chord-wise position further aft from the apex. The primary separation line of has no longer fixed at the leading edge but in the region close to it [5]. The origin of the primary vortex moves towards the apex of the wing [7] [8] [11], if the angle of attack is increased. Luckring [8] also showed that the upstream progression of the primary vortex on the blunt-edged delta wing is sensitive to Reynolds number.

The measurement of pressures in the leading edge region can predict the development of leading edge separation on blunt-edged delta wing. This paper aims to discuss the correlation between the leading-edge pressures coefficient on the development of the vortex primary. The effects of angle of attack and Reynolds number on the development of the primary vortex will also be discussed in this paper.

2 Model and Experimental Set-up

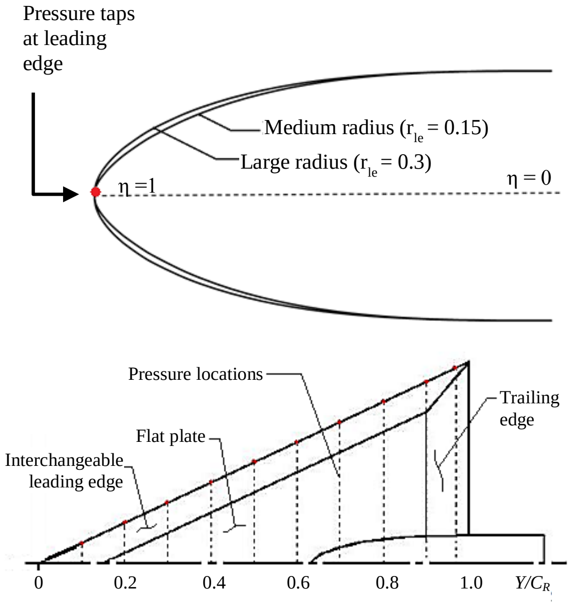
The model used in this experiment was replicated from the original NASA geometry tested in NASA-NTF and NASA-LTPT wind tunnels [9]. Similar model was also used as a generic profile within the VFE-2 campaign. In UTM, the model has root chord length of 1.311 meter and maximum span of 0.611 meter. The model was designated with two sets of interchangeable leading edge; *medium-radius* and *large-radius* that correspond to ratios of the leading edge radii to the model aerodynamic chord of 0.15 and 0.3 respectively (Shown in Fig. 2).

Experiments were carried out in Universiti Teknologi Malaysia Low Speed Tunnel (UTM-LST) 1.5 *m* × 2 *m* × 6 *m* closed circuit wind tunnel. The wind tunnel has the maximum speed of 80 m/s. The model was mounted to three-strut-support system shown in Fig. 1. This three-strut-support system is then connected to 6-components external balance located underneath the test section. This system can measure forces and moments in 6-axis simultaneously. Test were conducted at corresponding Reynolds numbers of 1×10^6 and 2×10^6, 3×10^6 based on mean aerodynamic chord respectively, and the model was pitched from 0° to 25° in increment of 3°.

Fig. 1.Installation of UTM-VFE2 model in UTM-LST

The main objective of the experiment was to measure the surface pressure on the upper surface of the wing. For both wings (medium and large radii), there were approximately 100 pressure taps located on the upper surface of the wing located at 10 constant percent root-chord stations as shown in Fig.2. However, the effects of Reynolds number on the forces and moment and the pressures distributions on the upper surface of the wing has been discussed and can be refer as in references [13].

In this paper, in order to investigate the nature of leading edge separation, only the pressure tabs in the leading edge region at η=1 across the wing were analyze. The surface pressures were measured by flow kinetics pressure scanner and the data were processed into coefficient form.



Chordwise surface pressure locations:
Y/C_R = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.97

Fig. 2. Pressure Taps Locations, replicated from Chu and Luckring [6]

3 Results and Discussions

A technique discussed by Luckring [7] [8] [12] to assess the pressure coefficient is implemented again to identify the passage of separation in this paper. The equation used is:

$$C_{p,le}= C_0 - C_2 \sin^2 \alpha \qquad (1)$$

At low angle of attack, the leading-edge pressures will follow the trend of slender wing theory, and this indicates that the flow is attached to the wing surface. The leading edge pressure departures from the slender wing theory curve if the flow is separated. If the leading-edge pressure consistent with the theory curve, the separation occurred downstream from the measurement point or attached flow is exists in the region. The peak point indicates that the separation is occurred in the region.

3.1 Reynolds Number Effects on Medium-Radius Leading Edge Wing

The effects of Reynolds number on the onset of leading edge primary vortex for the medium-edged wing at five chord-wise stations is summarized in Fig.3. From the figure, at Y/C_R=0.2, it can be observed that the airflow remains attached to the surface even angle of attack is increased to α = 25°. At Y/C_R = 0.4, it is observed that the attached flow exists up to the angle of attack approximately about α = 9°.

At α=9°, a significant reduction in negative pressure indicates that the flow separation has originated at this position. This scenario has become more distinct at position Y/C_R = 0.5. Downstream, the effect of Reynolds number on the onset of leading-edge separation is shown to be more identical at all cases.

At Y/C_R = 0.8, by comparing the results at 1×10^6 Reynolds number and 3×10^6 Reynolds number, the figure showed that the increase in Reynolds number has caused the onset of separation delayed from α = 6° to α = 9°. The stronger ability of turbulent boundary layer to endure adverse pressure gradient has led this phenomenon.

It can be observed that the Reynolds number has less effect on the progression of the primary vortex for the medium-radius wing. The separation is observed to occur at the same angle of attack for three different Reynolds number respectively.

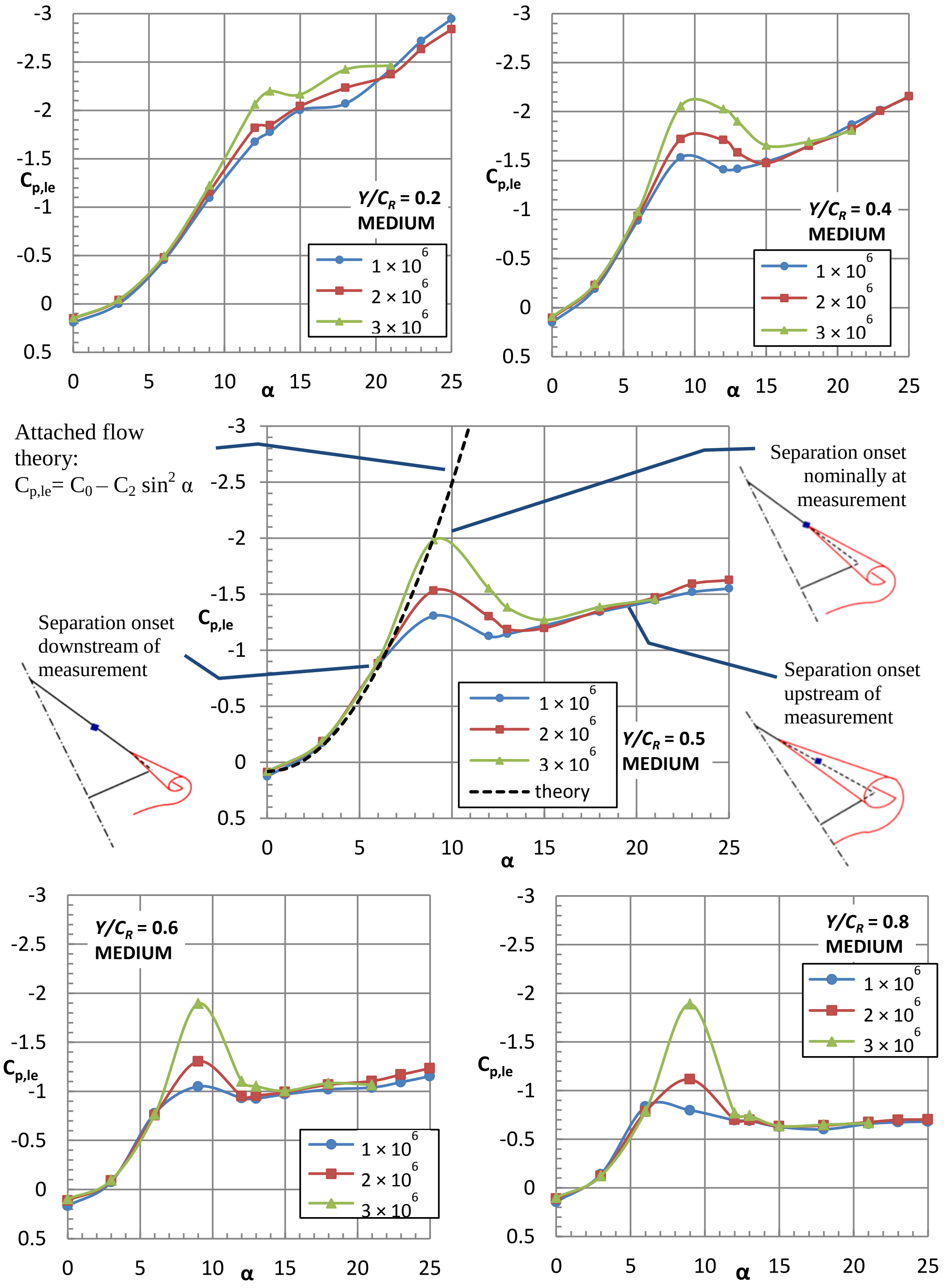
3.2 Reynolds Number Effects on Large-Radius Leading Edge Wing

The effects of Reynolds number is more distinct on the large radius wing compared to medium-radius wing, this is shown in Fig. 4. On this wing, the results showed that the leading edge separation is delayed if the Reynolds number increases. Generally, the flow remains attached to the surface for all 1×10^6, 2×10^6 and 3×10^6 Reynolds number at position 20% from the apex. Downstream to chord-wise position of Y/C_R = 0.4, a significant impact of Reynolds number is noticed. Here, each data is consistent with the theory up to certain angle of attack. For $R_{mac}=1\times10^6$ case, the flow started to separate at angle of attack of α = 10°. By increasing Reynolds number to 3×10^6, the onset of leading edge separation occurred at α = 18°. Further downstream and taken an example at Y/C_R=0.8, the highest Reynolds number delayed the onset of leading edge separation by approximately three degree angle of attack compared to the lowest Reynolds number in moderate range angle of attack.

At higher angle of attack, the results at 1×10^6 showed that the onset separation occurred earlier compared to those at higher Reynolds number. Fig. 4 also showed that results at 3×10^6 Reynolds number has delayed the separation onset by approximately five degree. The stronger ability of the turbulent boundary layer to endure the adverse pressure gradient delays the development of the primary vortex in the leading edge area. The upstream progression of the separation onset was course by the reduction of the attached flow region when the angle of attack is increased.

4 Conclusions

The results presented in this paper showed that the leading edge pressure can predict the nature of leading edge separation at different Reynolds number. The results obtained also depict that the origin of the primary vortex can be promoted towards the wing apex by decreasing the Reynolds number. The leading edge bluntness also influencing the onset of leading edge separation obviously. The effect of Reynolds number becomes more significant on the blunter wing. This technique also show that the onset of the vortex formations shift upwards by increasing the angle of attack.



Attached flow theory:
$C_{p,le} = C_0 - C_2 \sin^2 \alpha$

Separation onset nominally at measurement

Separation onset downstream of measurement

Separation onset upstream of measurement

Fig. 3. Reynolds Number Effects on Separation Onset on Medium Radius Leading Edge

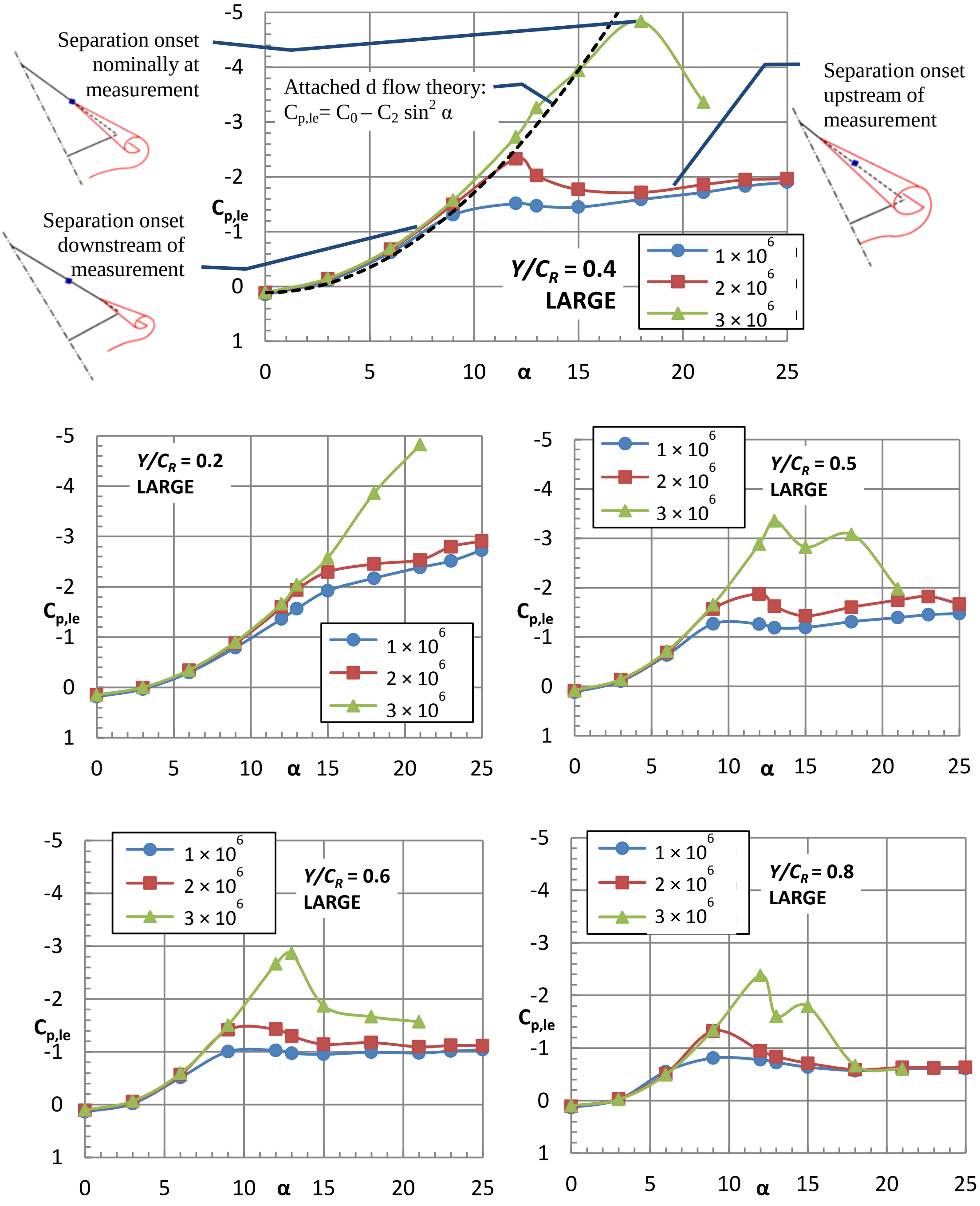


Fig. 4. Reynolds Number Effects on Separation Onset on Large Radius Leading Edge

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