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Effect of an end plate on surface pressure distributions of two swept wings

Mohammad Reza SOLTANI [a], Mehran MASDARI [b,*], Mohammad Rasoul TIRANDAZ [a]

[a] *Department of Aerospace Engineering, Sharif University of Technology, Tehran 19166, Iran*
[b] *Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran*

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Abstract A series of wind tunnel tests was conducted to examine how an end plate affects the pressure distributions of two wings with leading edge (LE) sweep angles of 23° and 40°. All the experiments were carried out at a midchord Reynolds number of 8×10^5, covering an angle of attack (AOA) range from −2° to 14°. Static pressure distribution measurements were acquired over the upper surfaces of the wings along three chordwise rows and one spanwise direction at the wing quarter-chord line. The results of the tests confirm that at a particular AOA, increasing the sweep angle causes a noticeable decrease in the upper-surface suction pressure. Furthermore, as the sweep angle increases, the development of a laminar separation bubble near the LEs of the wings takes place at higher AOAs. On the other hand, spanwise pressure measurements show that increasing the wing sweep angle results in forming a stronger vortex on the quarter-chord line which has lower sensitivity to AOA variation and remains substantially attached to the wing surface for higher AOAs than that can be achieved in the case of a lower sweep angle. In addition, data obtained indicate that installing an end plate further reinforces the spanwise flow over the wing surface, thus affecting the pressure distribution.

1. Introduction

Calculation of pressure distribution over airfoils operating in inviscid flow, is one of the classic problems of the fluid motion theory. Consequently, it has regained significance in designing swept wing aircraft.

The reasons for the application of swept wings to high-subsonic-speed aircraft are now well-established. Namely, a swept wing has a greater critical Mach number than that of a corresponding unswept wing. In addition, the variation of

* Corresponding author.
E-mail address: m.masdari@ut.ac.ir (M. MASDARI).

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pressure coefficient with Mach number for a given swept wing is smaller compared to that of an unswept wing with the same airfoil shape. Moreover, on a swept wing, the critical value of pressure coefficient is reached at a higher freestream Mach number. Furthermore, at low Mach numbers, the perturbation velocities are small compared with those of an unswept wing.

The tendency of a sweptback wing to tip stall is due to the induced spanwise flow of the boundary layer from root to tip. Since the tip of a sweptback wing is located aft part of the wing (behind the center of lift), it has the effect of moving the center of lift forward, causing a sharp pitch-up movement and thus making the stall worse than it was. The tendency to tip stall is the greatest when wing sweep and taper are combined.

There are many studies containing experimental pressure distribution measurements. For example, in 1952, a series of low-speed wind tunnel tests was conducted to determine boundary layer and surface pressure distribution characteristics of a family of sweptback wings. As a result, it was found that the experimental data would have had application in giving a better understanding of the viscous flow phenomena on sweptback wings, particularly in relation to the stall phenomena.[1] Likewise, in 1964, an experimental study was conducted on sweptback wings at the Ames Research Center to investigate the stall characteristics of swept wings.[2] In addition, in 1990, a comprehensive experimental study at the NASA Langley Research Center was conducted on F-14A variable swept wings modified for laminar flow, to assess the transition location under various conditions. Accordingly, left- and right-wing pressure distribution measurements at various Mach numbers and two different altitudes were used to give an explanation for the increased response amplitude of the right wing.[3] Furthermore, in 1997, a detailed investigation was conducted on F-111 aircraft modified with a variable-sweep supercritical mission adaptive wing (MAW) at the Dryden Flight Research Center, to improve the aerodynamic characteristics.[4] Moreover, in 2011, a series of experimental studies was conducted to examine the flow field over a swept wing under various conditions at Sharif University of Technology. Subsequently, measurements of pressure distribution were used to predict the transition point at each chordwise section.[5] Further, surface pressure distribution over a swept wing was exerted by Yen and Hsu[6] to investigate the effects of angle of attack α and chord Reynolds number Re_c on vortex shedding and aerodynamic coefficients.

On all subsonic wings there is a tendency for a secondary flow to develop from the high-pressure region below the wing round the wingtip to the relatively low-pressure region on the upper surface.[7] At a positive lift condition, the flow close to the tip of a three-dimensional wing tends to curl around the tip, because the flow is forced from the lower surface region (high-pressure side) to the upper surface region (low-pressure side) in a circular fashion (Fig. 1). This tendency for the flow to leak around the tip causes a circular three-dimensional flow pattern named vortex, which features a low-pressure core. Viewed from behind, the port wing tip vortex rotates clockwise and the starboard vortex rotates counterclockwise. Aircraft that encounter the wing tip vortices of large preceding aircraft can experience severe upward or downward loads as well as an overpowering rolling moment.

The research on the wing tip vortices began in the fifties and it is still an ongoing study because of its wide range of applications and because of the big number of fluid dynamic features

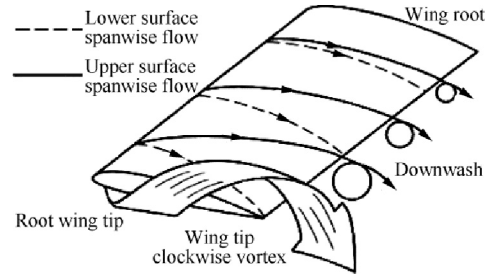

Fig. 1 Wing tip vortex.

that it implies: vorticity sheet rolling up, multiple vortex system, high turbulence level and relaminarization, diffusion, decay, collapse, instability and merging of vortices are just a few numbers of the aspects that coexist in this phenomena.[8]

Significant efforts have been utilized to investigate the formation and decay process of a wing tip vortex. Some of those efforts have been summarized by Spalart.[9] Winglets, end plates, tip sails, wing-grids, and blowing jets are typical examples of mechanisms for wing tip vortex control. They are effective in decreasing the strength of the trailing wing tip vortex and reducing the induced drag.[10]

The effect of eliminating wing tip vortices on aerodynamic characteristics has not been fully investigated until now. Only few experimental investigations on the effect of an end plate were conducted by Fink and Lastinger[11] and Carter.[12] Fink and Lastinger performed a series of wind-tunnel investigations to determine the ground effect on the aerodynamic characteristics of thick and highly cambered wings with various aspect ratios. Further, in 2008, a numerical analysis was performed to investigate the aerodynamic characteristics and static height stability of an end plate on an aspect-ratio-one wing in ground effect.[13]

End plates are commonly installed on aerodynamic models to mitigate three-dimensional end effects. Furthermore, experimental studies on flow development over non-circular geometries have similarly found that improved mean spanwise uniformity can be achieved by installing end plates on these models.[14] Moreover, end plates have been used in a number of experimental studies on airfoils operating at low Reynolds numbers.[15–18]

It should further be noted that a preceding work done by Soltani et al.[19] has successfully investigated the influence of Reynolds number on the surface pressure distribution over the same wing models without an end plate. In addition, Pelletier and Mueller[18] investigated the effects of end plates on force balance measurements for a two-dimensional Eppler 61 airfoil model at chord Reynolds numbers between 40×10^3 and 100×10^3. As a result, they demonstrated that the presence of end plates has a strong effect on lift and drag coefficients at low Reynolds numbers.

The purpose of this investigation is to assess the effects of end plates on the surface pressure distributions of two sweptback wings. Static pressure distributions along three chordwise rows and similar pressure measurements along one spanwise direction are obtained at a midchord Reynolds number of 0.8×10^5 and at angles of attack (AOAs) ranging from $\alpha = -2°$ to $\alpha = 14°$.