Experimental Thermal and Fluid Science 99 (2018) 94–116

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Flow structure of a low aspect ratio wall-mounted airfoil operating in a low Reynolds number flow

M. Awasthi[a,*], D.J. Moreau[a], C.J. Doolan[a]

[a] School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney, NSW 2052, Australia

ARTICLE INFO

Keywords:
Low aspect ratio airfoil
Laminar separation
Tip vortex
Horseshoe vortex
Boundary layer

ABSTRACT

Measurements on a wall-mounted NACA 0012 airfoil with an aspect ratio (***AR***) of 0.5 operating in the low Reynolds number (274,000, based on chord) regime were performed. Measurements included oil flow visualizations and velocity data obtained with a combination of pitot and hotwire probes. Three different geometric angles of attack (α_g) equal to 0°, 5°, and 10° were considered and the effective angles of attack corresponding to these were quantified through measurements of the velocity vector in the potential flow around the airfoil. The flow around such a low ***AR*** airfoil is complex and can be three-dimensional across the span due to strong interaction between the junction, airfoil, and tip flows. In the mid-span region of the airfoil, laminar separation with and without reattachment was present on the suction-side and pressure-side respectively. The pressure-side separation, which is located near the trailing-edge, leads to vortex shedding in the near-wake of the airfoil. The character of this shedding, however, is different between $\alpha_g = 5°$ and 10°. Towards the airfoil root (at 25% span), this shedding is supressed by the turbulent junction flow. Towards the free-end of the airfoil (at 75% span), shedding is observed even in the absence of pressure-side laminar separation and may be attributed to the interaction between the spanwise tip flow and the suction-side separation bubble. The airfoil boundary layer in this region is also thinner compared to that at the mid-span point. Further towards the airfoil tip (at 90% span), the shedding still exists; however, its intensity and character are modified by the dominant vortex dynamics. In proximity to the airfoil tip, the velocity and turbulence are affected by both the primary and secondary vorticity for the highest angle of attack studied.

1. Introduction

Most airfoil performance studies focus on the high Reynolds number regime due to its application in large aero/hydrodynamic systems such as aircraft, submarines, and wind turbines. However, there are a number of applications (turbomachinery, unmanned aerial vehicles (UAV), ventilation systems etc.) in which airfoils may operate in the low-to-mid Reynolds number regime ($Re_c < 500,000$) where flow features such as laminar separation and transitional separation bubble predominate. The term 'transitional' refers to the case where the flow separation is accompanied by a transition to turbulence. This low Reynolds number regime is the focus of the present paper. A number of studies [1–8] have characterized the behavior of laminar airfoil boundary layer separation – both with and without reattachment. Most of these studies have been concerned with a conventional two-dimensional airfoil section. In practice, however, many applications involve airfoils with finite span that are wall-mounted in which case there is little information regarding the spanwise variation of the flow structure across the airfoil and in the near-wake.

In general, there are three flow regimes for a wall-mounted finite airfoil. These are the airfoil-wall junction flow (referred to as simply junction flow from hereon) consisting of a horseshoe vortex and possible separation near the trailing-edge; the mid-span flow whose structure depends upon the Reynolds number as described above; and the tip flow that consists of vortices formed as the flow wraps around the free-end of the airfoil. In some instances, the Aspect Ratio ($AR = s^2/S$, where s is the span and S is the planform area) is large enough so that these individual regimes may be considered isolated and studied separately. In fact, this has been the case in most studies and an understanding of these individual regimes is readily available (see Simpson [9] for junction flows, Green [10] for tip flows, and Carmichael [1] for low Reynolds number flow over a two-dimensional airfoil). Table 1 provides a summary of some relevant studies on the three flow regimes of an airfoil along with a few studies performed on a wall-mounted finite airfoil. The table is organized based on the flow regime which was studied i.e. two-dimensional airfoil flow, tip flow, and

* Corresponding author.
E-mail addresses: m.awasthi@unsw.edu.au (M. Awasthi), d.moreau@unsw.edu.au (D.J. Moreau), c.doolan@unsw.edu.au (C.J. Doolan).

https://doi.org/10.1016/j.expthermflusci.2018.07.019
Received 9 October 2017; Received in revised form 27 June 2018; Accepted 18 July 2018
Available online 26 July 2018
0894-1777/

Nomenclature

AR	airfoil aspect ratio
c	airfoil chord-length
C_f	skin friction coefficient
d	pitot-probe diameter
D	open-jet width
f	frequency in Hz
$F(x_1, x_2, x_3 \cdots x_n)$	derived quantity from independent measurements $x_1, x_2, x_3 \cdots x_n$
$G_{uu}(f)$	spectral density of streamwise velocity fluctuations
H	boundary layer shape factor
n_d	independent number of records used in ensemble averaging.
N	number of data points in a given record
p_a	atmospheric pressure
T_∞	ambient air temperature
$Re_L = U_\infty L/\nu$	Reynolds number based on a reference length L
s	airfoil span
S	planform area
t	maximum airfoil thickness
u	mean streamwise velocity
u_{max}	maximum velocity induced by horseshoe vortex
u'^2	averaged mean square value of fluctuating streamwise velocity
u_τ	friction velocity
U_∞	free-stream velocity
x, y, z	near-wake coordinate system
x', y'	boundary layer coordinate system
x_n, y_n, z_n	wind tunnel based coordinate system
$y_{u'^2_{min}}$	location of local-minimum turbulence intensity in the near-wall region
$y_{u'^2_{max}}$	location of local-maximum turbulence intensity in the near-wall region
α_e	effective angle of attack
α_g	geometric angle of attack
α_i	induced angle of attack due to open-jet curvature
δ	boundary layer thickness
δ^*	boundary layer displacement thickness
$\Delta()$	error in a quantity
Δp_p	pitot total and static pressure differential
Δp_t	tunnel total and static pressure differential
θ	boundary layer momentum thickness
ν	kinematic viscosity of air
ρ	density of air
$\sigma()$	uncertainty in a measured quantity
σ_*	dimensionless parameter used to obtain corrected angle of attack for a 2D airfoil in an open-jet flow
ψ	local flow deflection angle in the potential flow around the airfoil

junction flow. For each study, the AR and Reynolds number based on airfoil chord (Re_c) are listed. Additionally, for junction flow studies the incoming, undisturbed boundary layer thickness (boundary layer thickness in absence of the airfoil at the airfoil nose location) to span ratio (δ/s) is also listed. Note that the table mainly focuses on studies concerned with the flow behavior near the airfoil surface or in the near-wake.

An analysis of Table 1 shows that some studies performed on the tip and junction flow have used low AR ($AR < 1.0$) airfoils but have not considered the flow across the entire span. A notable exception is the work by Huang and Lin [11] who measured the flow structure and wake vortex shedding characteristics across the span of a NACA 0012 airfoil. However, their study was on a high AR ($AR = 5.0$) airfoil and thus the three flow regimes may be considered separately. Nonetheless, their results show that for a NACA 0012 airfoil with a laminar separation bubble (which is of interest in the present work), the junction flow inhibits flow reattachment and the tip flow delays it. These results suggest that, for sufficiently low AR, such interactions could alter the flow-field across the airfoil span. Some junction flow [12–15] and tip flow [16] studies have considered airfoils with $AR< 1.0$ but the span-wise variation in flow structure was not examined in these studies. Also note that Shizawa et al. [15] did consider a very low AR ($AR = 0.3$) airfoil, however, the airfoil was a flat plate which can be expected to behave differently compared to a conventional airfoil due to the absence of a streamwise pressure gradient. The parameters used in the present study are listed at the bottom of the table. These parameters were chosen to fill the aforementioned knowledge gap by studying the flow structure across the span of a NACA 0012 airfoil with $AR = 0.5$.

The low Reynolds number flow over two-dimensional airfoils is characterized by the presence of laminar boundary layer separation which may occur on both the suction and pressure-sides of the airfoil [4]. The separated shear layer may or may not reattach to the airfoil surface depending on the Reynolds number and angle of attack. In general, a laminar separation bubble, if present, moves upstream with increasing angle of attack and Reynolds number as shown by several previous studies [2–7]. Pröbsting and Yarusevych [4] provide a good description of the Reynolds number effect on the laminar separation process on both sides of the airfoil, see §3.4 in their paper. Yarusevych et al. [2] studied the laminar separation on a NACA 0025 airfoil for $55{,}000 \leq Re_c \leq 210{,}000$ and geometric angles of attack (α_g) equal to 0°, 5°, and 10°. They found that a laminar separation bubble exists on the suction-side of the airfoil at $Re_c > 135{,}000$, 150,000, and 175,000 for $\alpha_g = 0°$, 5°, and 10° respectively. At Reynolds numbers below these, laminar separation occurred without reattachment. They found that the flow disturbances lead to a shear layer roll-up in both cases. These roll-up vortices then merge together during the transition to turbulence, before being broken down to smaller scales by the transition process. Therefore, they concluded that an interaction of the vorticity generated by the separated shear layer with that generated in the airfoil near-wake is only possible at lower Reynolds numbers where the separated shear layer does not reattach to the surface. This is also the reason why they found the wake vortices to be less coherent with smaller length scales when the separation bubble was present on the airfoil surface than when the separation occurred without reattachment. A similar breakdown of coherency in transitional separated laminar flow was also observed by Kirk et al. [7]. In the case of a low AR airfoil, the three-dimensionality generated due to the tip and junction flows can be expected to alter the characteristics of the laminar separation on both sides of the airfoil. This effect could particularly be strong when the separation occurs near the trailing-edge, thereby modifying the shedding characteristics in the wake of the airfoil.

The three-dimensionality of the flow towards the free-end of a wall-mounted airfoil arises due to the formation of tip vortices at both zero-lift and lifting conditions. At lifting conditions, the cross-flow from pressure to suction-side, due to the pressure differential, is the source of the tip vortex; while at zero-lift conditions the non-parallelism between the free-stream flow and the flow over the airfoil surface generates two vortices of opposite signs on either side of the airfoil [16]. The tip vortices roll-up in the near-wake past which a diffusion process leads to a decay or breakdown of the vortices in the far-wake. The evolution of tip vortices in the wake and their decay has been a focus of numerous studies due to its implications in aircraft safety and downstream wake interactions such as those in wind farms. Spalart [17] provides a detailed review of the downstream tip vortex behavior in the context of commercial aircraft. Compared with downstream tip vortex behavior, studies on the formation of this vortex and its behavior in close