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# A study of long separation bubble on thick airfoils and its consequent effects

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A B S T R A C T

A parametric study has been performed to analyse the flow around the thick-symmetric NACA 0021 airfoil in order to better understand the characteristics and effects of long separation bubbles (LoSBs) that exist on such airfoils at low Reynolds numbers and turbulence intensities. In the article, the prediction capabilities of two recently-developed transition models, the correlation-based $\gamma$–$Re_\theta$ model and the laminar-kinetic-energy-based $\kappa$–$\kappa_L$–$\omega$ model are assessed. Two-dimensional steady-state simulations indicated that the $\kappa$–$\kappa_L$–$\omega$ model predicted the separation and reattachment process accurately when compared with published experimental work. The model was then used to study the attributes and the effects of LoSBs as a function of the angle of attack, freestream turbulence intensity and Reynolds number. It was observed that LoSBs considerably degrade the aerodynamic performance of airfoils and lead to abrupt stall behaviour. It is, furthermore, illustrated that the presence of the LoSB leads to an induced camber effect on the airfoil that increases as the airfoil angle of attack increases due to the upstream migration of the bubble. An increase in the Reynolds number or turbulence levels leads to a reduction in the bubble extent, considerably improving the airfoil performance and leading to a progressive trailing-edge stall.

## 1. Introduction

Separation bubbles are generated primarily in applications involving low Reynolds number flows with large pressure gradients such as compressor blades in turbo-machines, high-altitude unmanned-air-vehicles, micro-air-vehicles and wind turbines (Lin and Pauley, 1996). The presence of the separation bubble is generally considered undesirable since it can impact the aerodynamic efficiency and stall behaviour of airfoils (Nakano et al., 2007; Zhang et al., 2008). The bubble can alter the flow at low Reynolds numbers and can consequently have adverse effects on the performance of the machine. Difficulties can also arise during airfoil testing in wind tunnels for applications involving high Reynolds number flows due to undesirable scale effects since most experimental wind tunnels operate in low Reynolds number regimes (Lissaman, 1983; Ol et al., 2005). The traditional methods to avoid these scale effects such as the addition of roughness strips and trip wires on airfoils or the addition of freestream turbulence also add a degree of complication and uncertainty to the process. Therefore, the characteristics of the separation bubble and its effects need to be understood well to improve the design methodology of airfoils.

The most prevalent type of transition observed on airfoils and wings at low Reynolds numbers is the separation-induced transition. Separation-induced transition primarily occurs when a laminar boundary layer is exposed to large adverse pressure gradients, such as those near the leading edge of airfoils, resulting in its separation. The separated shear layer then undergoes transition due to amplification of velocity disturbances in the flow (Alam and Sandham, 2000a). The resulting turbulent shear layer reattaches some distance downstream resulting in the formation of an enclosed region commonly referred to as a separation bubble. The primary aspects of separation-induced transition, adapted from Horton (Horton, 1968), are illustrated in Fig. 1.

The location and size of the separation bubble is a function of the airfoil profile, freestream Reynolds number, turbulence intensity and the angle of attack (Tani, 1969; Swift, 2009). Separation bubbles can be classified either as short or long based on their chordwise extent and consequent effects on an airfoil pressure and velocity distributions. A short separation bubble (SSB) encompasses a chordwise extent of less than one percent and therefore does not influence the pressure distribution around the airfoil to a large degree (Tani, 1961). After transition occurs in the separated

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shear layer, the pressures start to return to the inviscid distribution that would exist if there was no bubble present (Katz and Plotkin, 1991). On the other hand, a long separation bubble (LoSB) can cover several percent of the airfoil chord and, therefore, severely affects the pressure distribution and the forces generated by the airfoil. Due to increased interaction with the exterior flow, the pressure distribution may be modified to such a large extent that it may be substantially different compared to the inviscid values (Gaster, 1966). The effects of both types can clearly be seen in Fig. 2 where it can be observed that the presence of the separation bubble results in a zero pressure gradient region due to flow stagnation inside the bubble (Gaster, 1969). Therefore, once the flow separates, the pressure barely changes due to the very low flow velocities and the relatively low streamline curvature in the free-stream flow. As shown by Bursnall and Loftin (1951), the flow is fully turbulent prior to reattachment, indicating that it is likely the transition process aids in the shear layer reattachment.

SSBs are commonly observed on thin airfoil sections near the leading edge where large pressure gradients exist and have been studied extensively (Crabtree, 1959; Von Doenhoff, 1938; Tani, 1939; Owen and Klanfer, 1953). It has been shown that an increase in the angle of attack or a reduction in the Reynolds number can lead to the 'bursting' of the bubble resulting in the formation of a LoSB or an unattached free shear layer (Gaster, 1969). Therefore, the LoSBs are considered as the precursor of thin airfoil stall (Bak et al., 1998). On the other hand, the effects of LoSBs have not been studied in much detail since it is believed that these exist only due to the bursting of SSBs. However, literature survey and experiments have revealed that long bubbles can exist on the suction side of thick airfoils at low Reynolds number and their presence dictates the aerodynamic efficiency and stall behaviour of thick airfoil sections (Jacobs, 1932; Raghunathan et al., 1988; Swalwell et al., 2001; Hansen et al., 2011). Therefore, it is important to understand the global characteristics of a long separation bubble in order to improve the understanding of its consequent effects on the performance of an airfoil at low Reynolds numbers. Such a study will aid in the selection of appropriate control techniques to avoid the possible losses incurred by the presence of LoSBs.

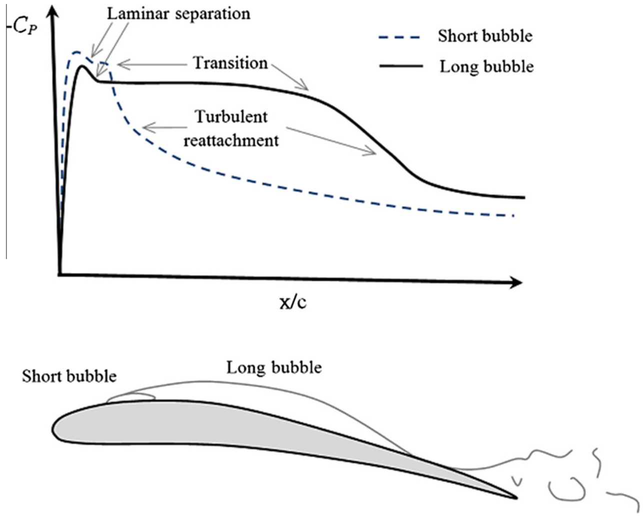

**Fig. 2.** The resultant pressure distribution on an airfoil due to presence of a short and long separation bubble.

In aerospace applications, parametric studies are most conveniently performed using numerical modelling techniques. Efforts have been made by several researchers to understand the characteristics of laminar separation bubbles. Marxen et al. (2004) performed Direct Numerical Simulation (DNS) of flow over a flat plate in order to observe the basic characteristics of separation-induced transition. Galbraith and Visbal (2008) conducted Large Eddy Simulation (LES) in order to determine characteristics of the separation bubble on the SD7003 airfoil. However, the use of DNS and LES for wall-bounded flows requires prohibitively long run-times and, therefore, these methods are not currently being used for purposes other than research. On the other hand, RANS-based approaches coupled with linear-stability theory, offer an attractive alternative for prediction of separation-induced transition (Windte et al., 2006; Radespiel et al., 2007; Lian and Shyy, 2007). In the present article, two recently-developed RANS-based transition models, the $\gamma$–$Re_\theta$ model (Menter et al., 2006) and the $\kappa$–$\kappa_L$–$\omega$ model (Walters and Cokljat, 2008) have been tested and compared. Both models have been studied extensively against standard test cases and have been shown to predict the transition onset and extent with reasonable accuracy (Walters and Cokljat, 2008; Langtry et al., 2006; Menter, 2011). However, these RANS-based models have not been compared with each other before. The $\gamma$–$Re_\theta$ model has been shown to have superior prediction capabilities compared to other correlation-based models (Suluksna and Juntasaro, 2008). On the other hand, the $\kappa$–$\kappa_L$–$\omega$ model focuses on the theory behind the model, instead of the results; however, there is little proof of the models' general applicability (Turner, 2012). Therefore, the two transition models have been assessed and compared in the current paper for the flow around NACA 0021 airfoil, based on the criteria established by Zingg and Godin (2009) for turbulence model assessment. In addition to this, a detailed analysis has been performed to study the characteristics of the LoSB and its effects on the performance of the NACA 0021 airfoil as a function of Reynolds number, freestream turbulence intensity and angle of attack. A peculiar effect of the LoSB has been noted in the present work and is discussed in detail in the article.

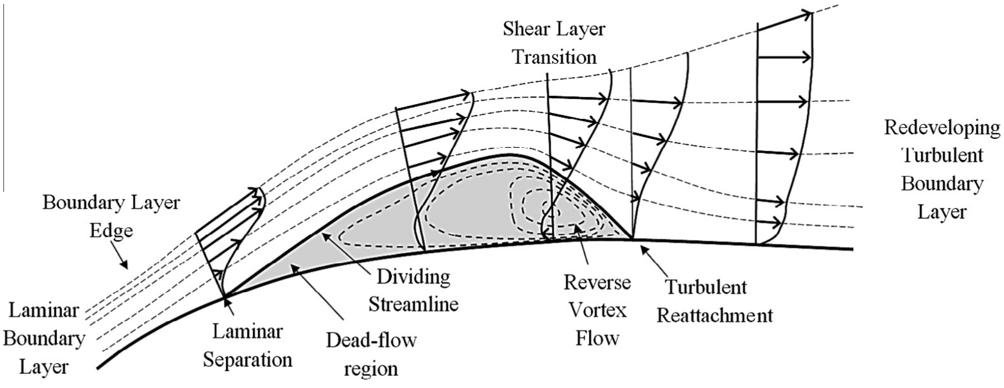

**Fig. 1.** Separation-induced transition, reproduced from Horton (1968).