Chapter 1

Introduction

1.1. A short history

The first sustained flight by the Wright brothers in 1903 marked a historic day in human achievement and ingenuity. Momentous as the achievement was, the Wright brothers did not truly invent the modern airplane. Their achievements were the fruition of nearly a century of aeronautical research, starting perhaps with Sir George Cayley, who is considered the first true aeronautical engineer and also been called the "father of aerial navigation" (Gibbs-Smith 1962). The principal components of the modern aircraft were laid down by George Cayley by 1799. Prior to Cayley, the ideas for mechanical flight tended towards flapping wings, where the flapping motion produced both propulsion and lift. George Cayley was the first to break the unsuccessful chain of thought and separated the two aspects of flight into distinct systems. His triple paper "On Aerial Navigation" published in Nicholason's *Journal of Natural Philosophy, Chemistry and the Arts* on November 1809, February and March 1810 (Cayley 1809-10) mark one of the most important works in aeronautical history. In the works, Cayley states for the first time, the principle of lift generation *i.e.* the formation of a low pressure region on the upper surface of the wing. His paper elaborates on the separation of lift from propulsion and also goes on to talk about flight control and airplane stability. Later in his life, he proposed the concept of multiplanes (multiple wings mounted on top of each other) and built the first glider triplane named the "boy carrier" in 1849.

Several investigators followed the quest of "aerial navigation". Otto Lilienthal was the first to design and successfully fly controlled gliders in 1891, going on to make over 2500 successful glider flights. Octave Chanute brought aeronautics research to America and designed a biplane glider which directly inspired the designs of the Wright Brothers. Samuel Pierpont Langley was a contemporary of the Wright brothers who built and tested several powered model airplanes. His success in achieving powered flight directly influenced and encouraged the Wright brothers. The final historic achievement of successful powered flight was achieved by the Wright brothers. On December 17^{th} 1903, a gasoline powered biplane by the name Wright Flyer I (figure 1.1) took flight in (modern day) Kill Devil Hills, North Carolina, ushering forth the era of practical human flight.

Figure 1.1: First flight of the Wright Flyer I, December 17, 1903, Orville piloting, Wilbur running at wingtip. Image from Wikipedia, the free encyclopedia (2017*b*).

1.2. Modern aircraft design

Since that fateful day, modern airplanes have been used in a variety of different conditions, varying from commercial passenger planes, to supersonic military aircrafts (NASA 2014), to endurance flights around the world lasting 9 days (Blakeslee 1986). The myriad uses have have resulted in various challenges that the aircraft designers have to had to overcome. One significant challenge has been due to the dynamic interaction of air flow with the airplane structures, now studied under the field of aeroelasticity. These problems came to the fore as the design speed of aircrafts increased over the years and designers came to favor monoplanes over the biplane design. An early example was that of the Fokker D-8 German aircraft during World War I which suffered wing failure under steep dives, which was the first documented case of static aeroelastic effects.

Today the designers of commercial aircrafts face another challenge brought about by global climate change and rising oil prices. With the realization of the contribution of the aviation industry towards global climate change (Green 2008), aircraft designers now face a need to significantly improve the fuel efficiency of commercial aircrafts in a bid to reduce the carbon footprint of the industry. In an effort to quantify the opportunities of achieving such an improvement, Schrauf (2005) showed a break-down of the drag experienced by a typical transport aircraft highlighting that frictional drag accounted for more than half the drag experienced by the aircraft. Clearly a favorable modulation of the boundary layer over the wing could help achieve large improvements in fuel efficiency. The modulation could come in the form of effective flow control strategies, or with wing design strategies such as the use of natural laminar flow (NLF) airfoils. Both Schrauf (2005) and Green (2008) push forward the idea that NLF airfoils and laminar flow control strategies are the low-hanging fruit in the goal of higher fuel efficiency and a concerted effort into addressing the engineering challenges for practical implementation must be made. Some of these challenges may require revisiting the aeroelasticity problems from the perspective of laminar wings. However laminar flow at high Reynolds numbers is susceptible to destabilization and may not always be possible, thus turbulent drag reduction, need to be used effectively where needed (Bushnell 2003). Whatever the form of drag reduction that may finally be implemented on a particular aircraft, the understanding of developing boundary layers over wings (including the influence of control strategies) occupies a central position if the goal of higher fuel efficiency is to be realized. With this goal in mind, the current thesis work aims to further the understanding of developing boundary layers over airplane wings, focusing on two particular aspects -

- Understanding the structure of the turbulent boundary layer developing over a wing section.
- Understanding the evolution of the developing boundary layer over a natural laminar flow airfoil in unsteady flight conditions.

1.3. Unsteady boundary layers

Unsteady aeroydnamic studies started with the emergence of aeroelastic phenomenon in the early part of the 20^{th} century. With the gradual shift to monoplane designs, the inherent high torsional stiffness of biplanes was lost and aerodynamic instabilities, such as the one experienced by the Fokker D-8 became important. Pioneering works of Glauert (1930); Karman & Sears (1938); Theodorsen (1935) *etc*, provided the insight and modeling of such unsteady aerodynamic behavior and by the 1940s the foundations of unsteady aerodynamics for incompressible attached flows had been laid down. The mathematical framework these unsteady aerodynamic theories relied on simple inviscid and quasi-steady assumptions, which proved to be highly attractive to the wing designers (Leishman 2000). Experimental corroboration by Halfman (1952) and Rainey (1957) further added support to the validity of the simple assumptions. Over the next few decades, investigations of unsteady aerodynamics shifted focus to the understanding of the dynamic stall phenomenon, with works of McCroskey *et al.* (1976); McCroskey (1981); McCroskey *et al.* (1982); McCroskey (1982); Carr *et al.* (1977); Crisler *et al.* (1994). A large body of work on unsteady separated flows was presented by Ericsson & Reding (1986, 1987, 1988*a*,*b*). The studies continue to this day with the works of Visbal (2011, 2014); Visbal & Garmann (2017); Dunne & McKeon (2015) and several other authors, a recent review can be found in Coorke & Thomas (2015).

However it appears that the aeroelasticity problem was not considered from the perspective of natural laminar flow airfoils. This is a surprising

Figure 1.2: North American P-51 Mustang. Image from Wikipedia, the free encyclopedia (2017*a*).

fact considering the P-51 Mustang (figure 1.2), a fighter aircraft in the Royal Air Force designed in 1940, incorporated a wing with a natural laminar flow airfoil section (Green 2008). The first aeroelastic study on laminar wings was performed as late as 2011 by Mai & Hebler (2011). This along with a subsequent investigation by Hebler *et al.* (2013), brought to light a peculiar characteristic of unsteady laminar wings, *i.e.* the presence of non-linearities in the unsteady aerodynamic forces. The classical unsteady aerodynamic theories did not predict non-linear unsteady responses and thus fail to account for such behavior. Inspired by this, Lokatt (2017) performed experiments on unsteady NLF airfoils and also found strong non-linearities in the aerodynamic forces. Consistent in the explanation for the non-linearities in all these studies was the role of transition over the wing surface. When transition on the airfoil suction-side was fixed (with a trip) near the leading edge, the non-linearities seemed to disappear. These results indicated a need for a more in-depth study of the evolving boundary layer in such unsteady laminar airfoils. Classical theories negate the role of the boundary layer by invoking the inviscid assumption and it is apparent that such an assumption is no longer be justified for laminar wings.

1.4. Boundary layers over a stationary wing

The understanding of the structure and scaling of wall-bounded turbulent flows has been in study for several decades and a complete understanding still remains far from complete. These flows have been studied with different canonical geometries such as channels (Kim *et al.* 1987; Moser *et al.* 1999; Lee

& Moser 2015), pipes (El Khoury *et al.* 2013; Jiménez & Hoyas 2008; Chin *et al.* 2015) and flat plates Spalart (1988); Schlatter & Örlü (2010); Eitel-Amor *et al.* (2014). For the case of spatially evolving boundary layers over a flat plate, the simplest canonical case involves boundary-layer evolution subjected to a Zero Pressure Gradient (ZPG). These flows may be uniquely characterized by a single parameter, *i.e.* the Reynolds number (Re), which is the ratio of the inertial and viscous scales of the flow. However practical flow cases are often influenced by pressure gradients. Such flow cases can no longer be uniquely defined using a single parameter. Clauser (1954) with intuitive reasoning proposed a concept of an equilibrium boundary layer which may be uniquely defined by two parameters, arguing that, if the ratio of the average pressure gradient force across the boundary layer and the viscous shear force at the wall remains constant the boundary layer would experience a similar flow history throughout its evolution. Thus the equilibrium pressure gradient boundary layers are uniquely defined by two parameters, namely the Reynolds number (Re) and the pressure gradient parameter, β defined as:

$$\beta = \delta^*(dp/dx)/\tau_w, \tag{1.1}$$

where δ^* is the displacement thickness, dp/dx is the pressure gradient and τ_w is the wall-shear stress. The parameter is commonly referred to as the Clauser parameter. A flow case with a constant Clauser parameter is categorized as an equilibrium boundary layer and a ZPG boundary layer is a special case of an equilibrium boundary layer with $\beta = 0$. In a theoretical analysis Townsend (1956*a*) showed that for a self-similar boundary layer, the Clauser parameter is indeed constant. Several works have focused on pressure gradient boundary layers ranging from theoretical studies by Townsend (1956*b*); Mellor & Gibson (1966), experimental works of Skåre & Krogstad (1994); Harun *et al.* (2013) and numerical simulations by Spalart & Watmuff (1993); Skote *et al.* (1998). The developing boundary layer over an airfoil however further increases in complexity since these boundary layers fall under the category of non-equilibrium boundary layers where the Clauser parameter is spatially varying. In such cases the flow history also plays a role in determining the local boundary layer properties (Clauser 1954; Bobke *et al.* 2017). Analysis of such flow cases becomes significantly more difficult since the local boundary layer parameters do not uniquely define the state of the boundary layer. Nonetheless the study of such boundary layers is important since generic boundary layers found in nature would belong to this category, including the boundary layers over wings. The boundary layer developing over the NACA 4412 airfoil has a special property that the spatially varying Clauser parameter is insensitive to Reynolds number. The presents us with the unique opportunity to study the Reynolds number effects of a non-equilibrium boundary layer with a constant pressure gradient history. That is indeed the methodology followed in this work. The developing boundary layer over a NACA 4412 wing section is analyzed at two different Reynolds numbers in order to understand Reynolds number effects.

Thesis structure. The thesis is structured as follows:

- An overview of the numerical method used for the simulations is given in Chapter 2.
- Chapter 3 gives an overview of the numerical simulations performed in the study.
- The main conclusions of the current work are given in Chapter 4 along with an outlook for future work.
- The next part of the thesis includes the individual papers and internal reports.