1 Introduction

1.1 Background

Flow control attempts to introduce perturbations into the flow field to alter the original flow development path to an ideal state. Thus, one can achieve desired goals, such as lift enhancement, drag reduction, vibration suppression, noise reduction, fuel and heat transfer enhancement, etc. In addition, the implementation of flow control is usually related to complex flow phenomena. Thus, flow control is of great significance for not only the development of the subject of fluid mechanics but also has great potential applications in engineering.

The most important application of flow control is in aviation, which is aimed to improve the performance of aircrafts. The origin of modern flow control could be traced back to 1904, when the boundary layer theory was developed by Prandtl. He was also considered to be the first one to use steady suction control to delay flow separation of diffusers and a circular cylinder (Joslin and Miller 2009). Since then flow control has developed in association with the development of the aviation industry. In particular, it has made great contributions to the advancement of aviation.

Flow control can improve the aerodynamic performance, safety and environmental performance of the aircraft. There are substantial data to prove this. A 1% reduction in the cruise drag of a large passenger aircraft could lead to about 1600 kilograms reduction of airplane empty weight or an increase of about 10 more passengers (Chen et al. 2009). In particular, a 1% drag reduction is equivalent to saving 57 000 liters aviation fuel for B737 and 380 000 liters for B747 per year (Ma and Cui 2007). Researches in Boeing Company (Garner et al. 1991) indicate that for a commercial jet transport, a 0.1 increase in lift coefficient is equivalent to saving airplane empty weight of about 630 kilograms at the constant angle of attack, a 1.5% increase in maximum lift coefficient is equivalent to about 3000 kilograms increase in payload at a fixed approach speed, and a 1% increase in the lift-to-drag ratio during takeoff is equivalent to about 1270 kilograms increase in payload.

Thus, flow control has attracted much attention by many research institutions. Many significant research projects have been conducted recently to advance the understanding and applications of flow control.

In 2001, the Group of Personalities formed by Philippe Busquin, who was the European Commissioner for Research, published a landmark report on “European

Aeronautics: A Vision for 2020," in order to make aviation better serve society's needs and for European Aeronautics to become a global leader in the field. In this report, several goals for performance of aircraft in 2020 were proposed, including a 50% reduction of noise, a 50% cut in CO_2 emissions per passenger kilometre, and an 80% cut in nitrogen oxide emissions. Flow control is definitely needed to achieve these goals. Thus, the European Union conducted a series of research projects associated with flow control in succession, including "AEROMEMS (Advanced Aerodynamic Flow Control using MEMS)," "AEROMEMS II," "AVERT (Aerodynamic Validation of Emission Reducing Technologies)," "PLASMAERO (Useful Plasmas for Aerodynamic Control)." Many institutes and universities were involved in the projects to advance the applications and validations of flow control techniques.

In 2006, the National Aeronautics and Space Administration (NASA) requested the National Research Council (NRC) to undertake a decadal survey of civil aeronautical research and technology priorities that would help NASA fulfill its responsibility to preserve USA leadership in aeronautical technology. This report called "Decadal Survey of Civil Aeronautics: Foundation for the Future" presented a set of strategic objectives for the next decade of research and technology. It listed the top 11 challenges for aerodynamics and aeroacoustics, and the second and the fourth are closely related to flow control, namely "Aerodynamic performance improvement through transition, boundary layer, and separation control" and "Aerodynamic designs and flow control schemes to reduce aircraft and rotor noise." Under the heading of aeronautical technology, NASA established a "Vehicle Systems Program" to conduct fundamental research on advanced technologies for future flight vehicles (Washburn et al. 2002). It was indicated that several components of this program, such as "Breakthrough Vehicle Technologies Program (BVT)," "Ultra Efficient Engine Technology Program (UEET)," and "21st Century Aircraft Technology Program (TCAT)," needed the support of flow control. Following these projects, the NASA Langley Research Center, Air Force Research Laboratory, Boeing Company conducted a series of investigations that supported improved high-lift capability, drag reduction, noise suppression, propulsion/airframe integration, and maneuvering performance.

After 100 years of development of the modern aircraft, it has become more and more difficult to reduce drag and noise by optimizing aircraft design only. Thus, flow control provides an approach to further improve the aircraft performance. Though it meets some difficulties in both techniques and technologies for engineering applications, a few flow control techniques have been used in aircrafts up to now, such as high-lift airfoils, vortex generators, and wing tips, etc. It is suggested that flow control is of importance because of its great potential to significantly advance the development of aviation.

1.2 Classification

There are many different kinds of flow control techniques, which could be classified into different groups according to certain criteria. For the purpose of flow control, techniques could be used to increase lift, reduce drag, suppress vortex-induced-vibration, reduce

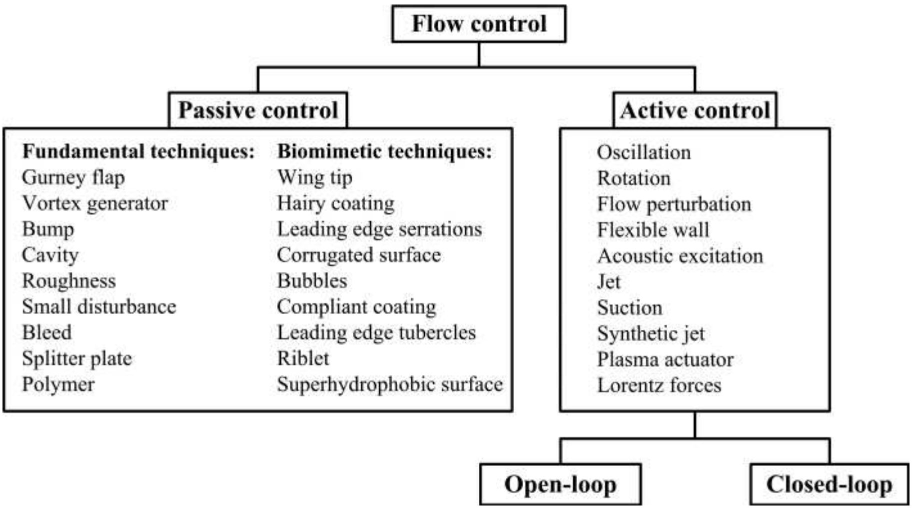

Figure 1.1 Categorization of flow control techniques.

noise, enhance mixing, etc. Some of the goals are related with each other. We can increase the lift coefficient of airfoils by either reducing flow separation or increasing the circulation. The former is only effective when there is a flow separation, for example at post stall angles of attack, meanwhile a reduction in drag could also be achieved. On the other hand, circulation control can increase the lift coefficient from low to high angles of attack. Pressure difference drag could be reduced by delaying flow separation, while the reduction of friction drag is related with boundary layer control. When the intensity of wake vortex shedding is weakened, it might be beneficial for reducing vortex-induced-vibration and noise. In comparison, stronger vortical structures could enhance mixing and heat transfer.

We can also classify flow control techniques according to the application fields, such as aviation, space, turbomachinery, combustion, building, transportation, etc. The appropriate flow control techniques might be different for various fields. However, it is essential that we should first understand the fundamental characteristics of the techniques and then propose the optimal control strategy.

Besides the categories mentioned above, flow control techniques are most frequently classified into passive and active based on energy input, as shown in Figure 1.1. Passive flow control techniques need no energy, are easy to implement, but cannot be changed during the control process. Active techniques need extra energy, and can be adjusted during the control process and thus be implemented in real-time and unsteady flow control. Thus, effectiveness and efficiency for the active techniques is usually more significant than that for passive ones.

There exist different kinds of passive flow control techniques. In general, we can further distinguish them into different groups based on their origin. One group is developed based on our understanding of flow physics, which is called the fundamental technique. For example, we already know that vortical structures may be

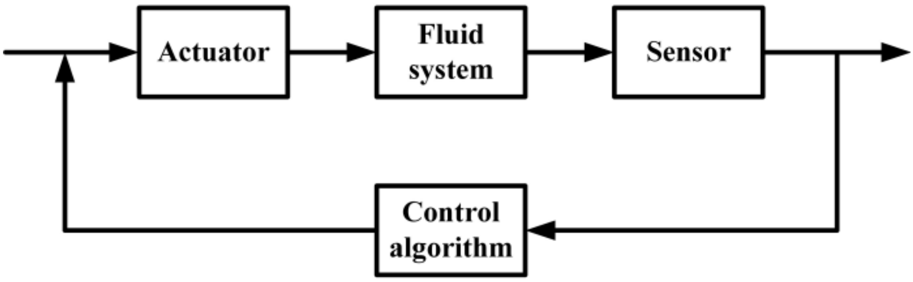

Figure 1.2 Schematic of the closed-loop control algorithm.

induced by the instability of the separated shear layer for flow over an object with adverse pressure gradient, thus a small inclined plate placed in the crossflow could induce the streamwise vortex. The idea of control by vortex generators has therefore been proposed.

The other group may be derived from nature, from animals to plants. Through natural selection living organisms develop their own shapes and organs with specific features, that are expected to be optimal and adaptive for organisms in certain environments. Thus, we can learn from them to copy or mimic these features to improve the performance of man-made systems. Accordingly, different kinds of biomimetic flow control methods have been proposed.

The active flow control techniques are not only related to fluid mechanics but also to other disciplines. The essential factor of active flow control is to introduce perturbations into the flow fields, which could be achieved by methods based on mechanics, electronics, or electromagnetism, etc. For example, the traditional free jet is usually produced by a mechanical air bump. The synthetic jet could be produced by either a mechanical device or the combination of mechanics and electronics, namely MEMS (Micro-electro-mechanical system). The plasma actuator is related to electronics, and the Lorentz force to electromagnetism. In addition, acoustics, thermodynamics, and optics are also useful in developing effective active flow control techniques.

When active flow control is performed, it could be applied either in an open-loop or closed-loop approach. The open control implements actuation based on the scheduled program and the control parameters are not influenced by the control results. For the closed-loop control, however, the control parameters depend on information from the control system which in turn depends on the control. The schematic of the closed-loop control system is shown in Figure 1.2. A control system includes fluid system, actuator, sensor, and control algorithm. The fluid system stands for the flow field to be controlled. The actuator refers to the active flow control techniques, which could introduce excitation to the fluid system. The sensor measures some variables from the controlled flow, which are used as a reference to adjust the actuator parameters. The control algorithm is used to guide the operation of the actuator. Such a control approach is also referred as feedback control. It is different from feedforward control, where the sensor signal is based on the oncoming flow but not the controlled flow.

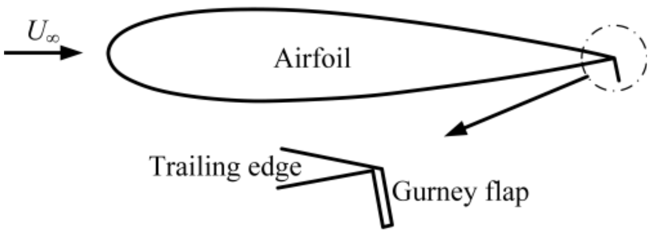

Figure 1.3 Schematic of a Gurney flap mounted on the pressure surface of an airfoil.

We will first present most of the passive and active flow control techniques briefly in this introductory chapter, and then some typical and important techniques will be introduced in detail in the main chapters.

1.3 Passive Flow Control

1.3.1 Gurney Flap

The Gurney flap is a simple device, such as a flat plate, which can be easily attached to the pressure surface of an airfoil, as shown in Figure 1.3. The size of the Gurney flap is only of the order of about 1% chord length of the airfoil, but can significantly increase the lift coefficient. There have been numerous works to show its effects on airfoils, wings and aircrafts, which has been reviewed by Wang et al. (2008). Under certain conditions, both the lift coefficient and lift-to-drag ratio could be increased, though there is a drag penalty. Thus, the Gurney flap shows great potential application to shorten the takeoff/landing distance of aircraft.

1.3.2 Vortex Generator

A vortex generator is usually a small device placed onto the wall, which can induce a streamwise vortex. There are many devices that can be used as a vortex generator, such as flat plate, wishbone, doublet, airfoil, wedge, ramp, etc. The devices are usually arranged in one row along the spanwise direction to induce a set of vortices, either in a co-rotating manner where each device is inclined in the same direction (Figure 1.4(a)), or a counter-rotating manner where a pair of devices induces vortices with different rotation directions (Figure 1.4(b)). The induced streamwise vortices have the great ability to enhance momentum mixing, which is beneficial for separation flow control. Thus, vortex generators have been applied in various fields for flow control, ranging from low-speed to high-speed fields, which has been reviewed by Lin (2002) and Lu et al. (2012).

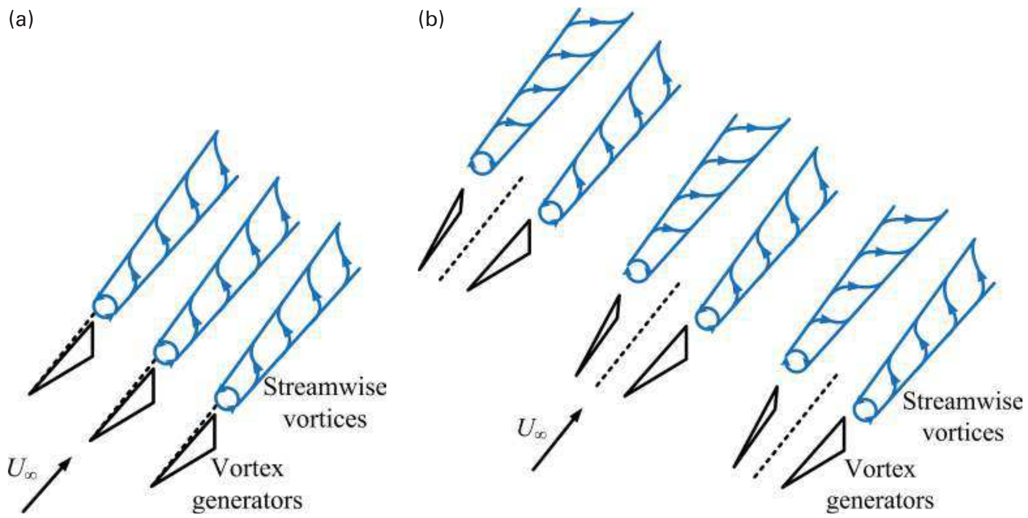

Figure 1.4 Schematic of vortex generators. (a) Co-rotating arrangement; (b) counter-rotating arrangement.

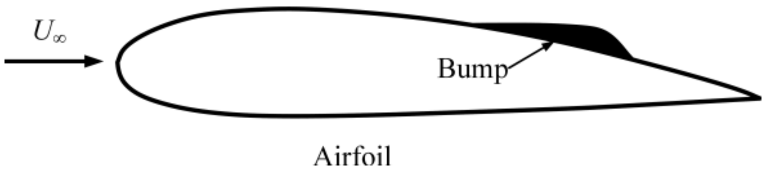

Figure 1.5 Schematic of an airfoil with a bump.

1.3.3 Bump

A bump is usually used to control the shock wave of a transonic airfoil and thus to reduce its drag. It is placed in the downstream of the normal shock wave over the airfoil suction surface, as shown in Figure 1.5. The bump could induce λ-shock structures that can reduce the impact of shock waves by replacing a single normal shock wave with several shock legs. The total pressure loss through a series of oblique shock waves is usually smaller than that across a normal shock wave, thus the wave drag can be greatly reduced. Milholen and Owens (2005) and Li et al. (2011) found that drag reduction of around 12%–15% could be achieved at Mach numbers of 0.73 to 0.78. Besides, the bump could also be used to delay buffet onset and expand buffet boundary (such as Tian et al. 2011).

1.3.4 Cavity

A cavity with trapped vortex is usually used for the control of airfoils. A cavity of suitable shape is positioned along the spanwise direction over the suction surface of

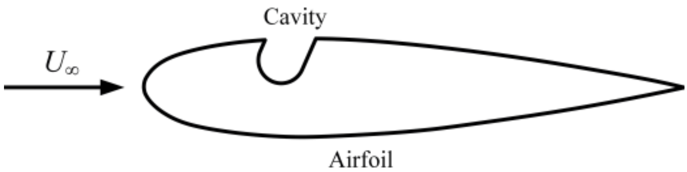

Figure 1.6 Schematic of an airfoil with a cavity.

the airfoil, as shown in Figure 1.6. A large-scale vortex will be induced in the cavity, creating a recirculation region closed by the dividing streamline (Lasagna et al. 2011). The flow over the airfoil suction surface will be modified. In particular, the flow over the airfoil with a cavity separates before the forward edge of the cavity at high angles of attack. The separated flow displays a strong interaction with the cavity, causing the flow to shed smaller-scale vortical structures than the airfoil without a cavity. Thus, the near wake becomes narrower and the lift-to-drag ratio is increased with cavity control, in comparison with the clean airfoil (Olsman and Colonius 2011). In order to stabilize the trapped vortex, additional blowing or suction control could be used, such as that conducted by Iollo and Zannetti (2001) and Olsman et al. (2011).

1.3.5 Roughness

There have been numerous works to show the effects of roughness on laminar flow, flow transition, and turbulent flow, such as those reviewed by Jiménez (2004). It is well known that roughness may promote flow transition, and one example is shown in Figure 1.7(a) for the golf ball, which has global dimples to make it a roughness surface. The dimples over the golf surface could accelerate flow transition to turbulence, which enhances momentum mixing to enable fluids to resist adverse pressure gradient. Thus, the flow may separate at around 120° from the front stagnation point, in comparison with the separation angle of about 80° for the laminar flow over a smooth ball. Thus, the golf ball has a smaller pressure-difference drag and could move further than a smooth one.

However, pioneer work conducted by Fransson et al. (2006) indicated that a row of cylindrical roughness elements placed on a flat plate (Figure 1.7(b)) with specific height and spacing could effectively delay flow transition. In particular, an original turbulent flow could be changed to a laminar flow. Subsequent studies have also indicated the effect of the roughness elements on the bypass transition and the turbulent flow.

1.3.6 Small Disturbance

A small disturbance may trigger the instability of the local flow to further influence the global field. Some examples of disturbance are the trip wire (Figure 1.8(a)) and the small

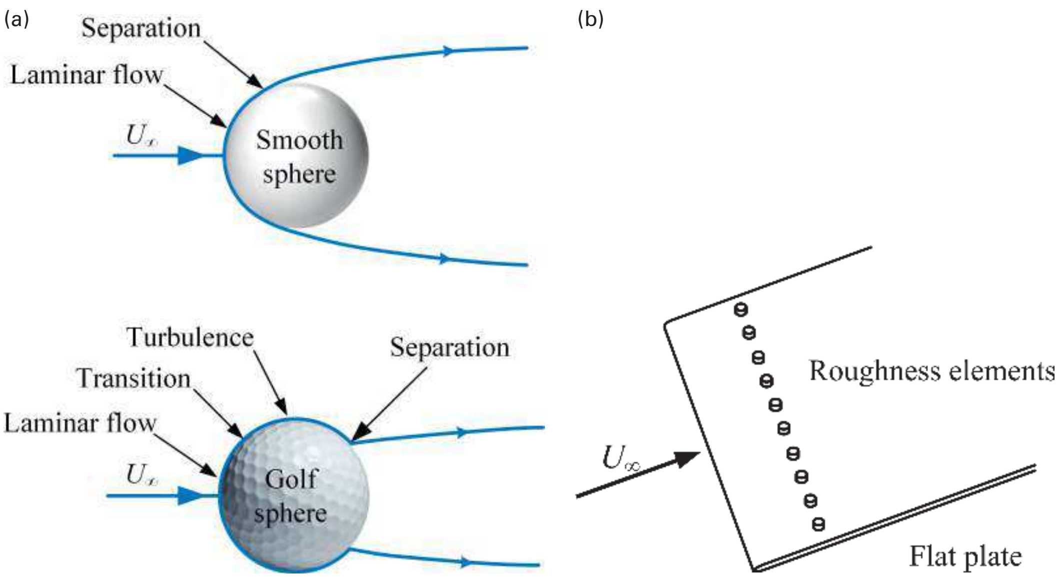

Figure 1.7 (a) Effect of dimples on a sphere. (b) Schematic of roughness elements placed on a flat plate.

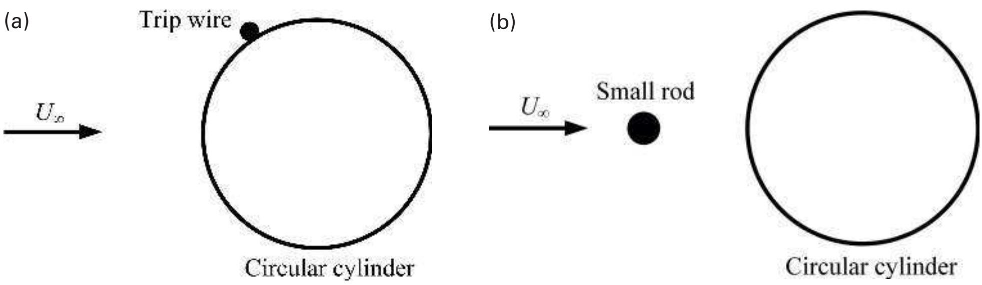

Figure 1.8 Schematic of a circular cylinder with a trip wire (a) and a small rod in the upstream position (b).

rod (Figure 1.8(b)). A trip wire is usually used to promote flow transition to turbulence for different objects, including a cylinder (such as Ekmekci and Rockwell 2010) and a sphere (such as Son et al. 2011). However, it is mostly used for the boundary layer experiment, when a turbulent flow is needed.

A rod is usually a much smaller cylinder in comparison with the scale of the controlled bluff bodies, including a square cylinder (such as Zhang et al. 2005), a circular cylinder (such as Wang et al. 2006; Zhang et al. 2006a), a disc (such as Zhang et al. 2006b; Wang et al. 2013b), etc. The small rod could be placed upstream or downstream of the bluff body with a staggered angle. The wake induced by the small rod may interact with the flow over the bluff body, which could result in a global variation of the bluff body's wake and a reduction in drag. For example, Zhang et al. (2005) and Wang et al. (2006) found that there were six different wake

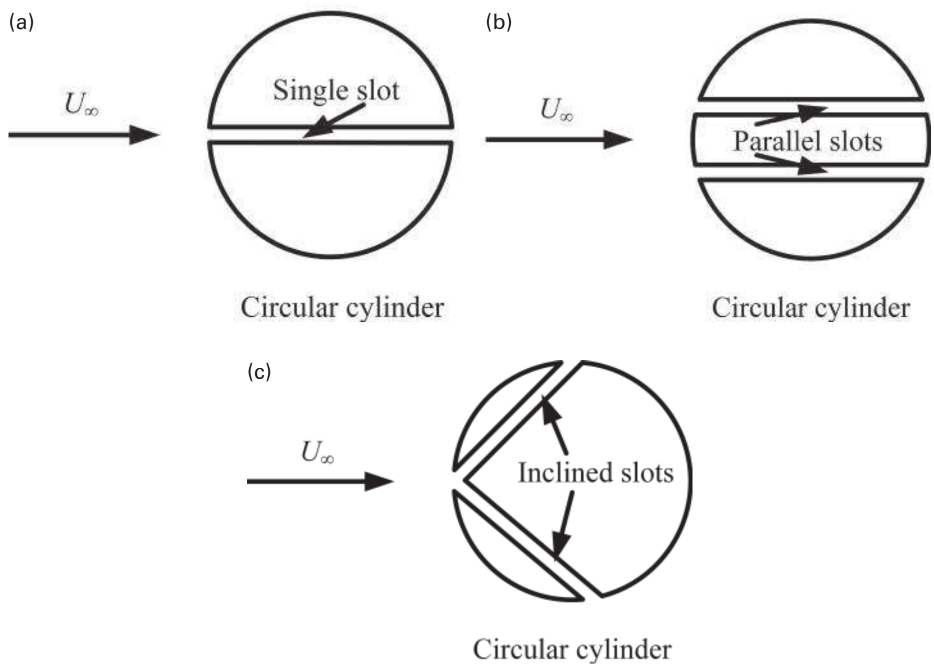

Figure 1.9 Schematic of a circular cylinder with bleed control. (a) One slot across the front and rear stagnations points; (b) two parallel slots; and (c) two inclined slots.

modes induced by a small rod upstream of the bluff body, namely cavity flow, wake impinging, wake merging, wake splitting, weak boundary layer interaction mode and negligible interaction. In particular, a maximum drag reduction by about 98% was found for the cavity flow mode.

1.3.7 Bleed

Bleed control is achieved by machining narrow slots across the controlled body. Fluids would flow across the slot and form a localized jet from the exit. One application is to control the circular or square cylinder, and there are several different arrangements of the slot. One slot could be across the front and rear stagnation points (such as Fu and Rockwell 2005; Baek and Karniadakis 2009), as shown in Figure 1.9(a). Also, two slots can be used, which could be parallel to the streamwise direction (such as Aydın et al. 2010), as shown in Figure 1.9(b), or with some inclined angle (such as Shi and Feng 2015). For all cases, the jets issuing from the slots will interact with the boundary layer or shear layer, leading to an ideal control effect. Baek and Karniadakis (2009) and Shi and Feng (2015) indicated that the bleed control could convert the original asymmetric vortex shedding mode to the symmetric one, which is beneficial for the suppression of vortex-induced vibration.

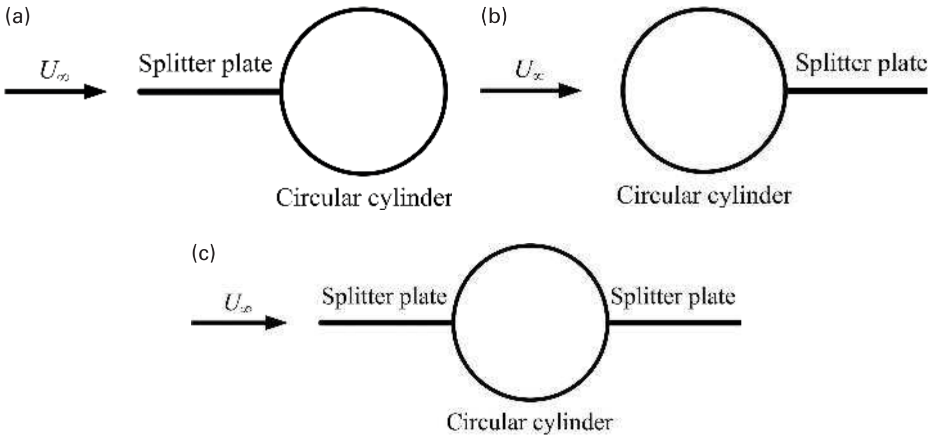

Figure 1.10 Schematic of a circular cylinder with splitter plates. (a) A splitter plate placed at upstream position; (b) a splitter plate placed at downstream position; and (c) two splitter plates placed at both upstream and downstream positions.

1.3.8 Splitter Plate

A splitter plate is a flat plate placed upstream (Figure 1.10(a)), downstream (Figure 1.10(b)), or both upstream and downstream (Figure 1.10(c)) of the object along the streamwise direction. Note that it is not necessary to connect the splitter plate to the controlled body surface; there could be a distance between them. Celik et al. (2008) indicated that the splitter plate upstream of the cylinder changed the flow dynamics of the downstream cylinder in the formation region. The splitter plate downstream of the cylinder may restrict the mutual interaction between the upper and lower shear layer, resulting in an elongated recirculation region, a larger vortex formation length, a weaker wake vortex strength, and a reduced drag coefficient, which have been found by Hwang et al. (2003), Akilli et al. (2005), Serson et al. (2014), among others. Hwang and Yang (2007) indicated that the upstream splitter plate reduced the stagnation pressure, while the downstream one increased the base pressure by suppressing vortex shedding. Thus, the combined effect with both upstream and downstream plates caused a significant drag reduction on the cylinder. Note that the splitter plate could be either rigid or flexible.

1.3.9 Polymer

Polymer is a transitional passive control technique for turbulent drag reduction. When the polymer additives are dropped in the fluids, the turbulent flow in the near-wall region might force the polymer to roll up chains, which are stretched in the mean flow direction, as shown in Figure 1.11. In this case, polymer chains exhibit characteristic length scales associated with the turbulent structures, which is related to drag reduction. It was found that minute concentrations of polymers could reduce the drag in turbulent flows by up to 80% (Procaccia et al. 2008). Thus, the study of drag reduction by polymer is important