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

https://doi.org/10.1017/9781316676448.002 Published online by Cambridge University Press

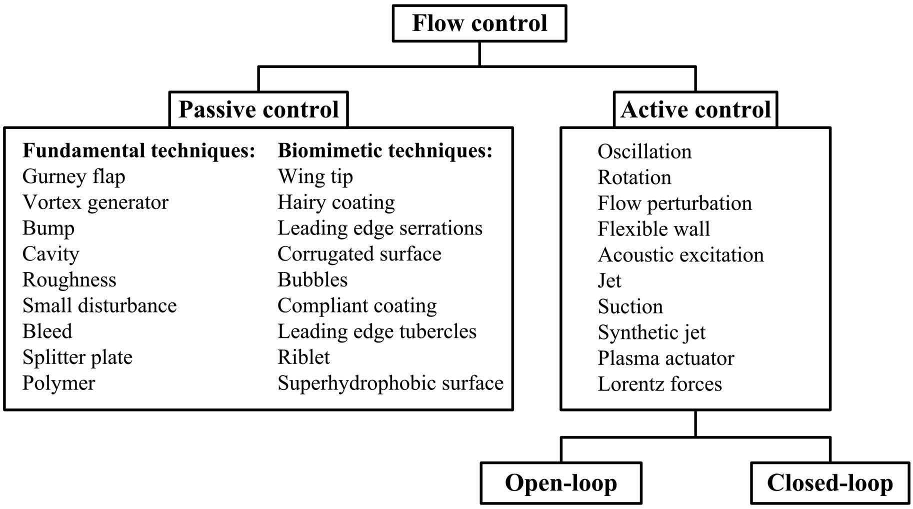

Figure 1.1 Categorization of flow control techniques.

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

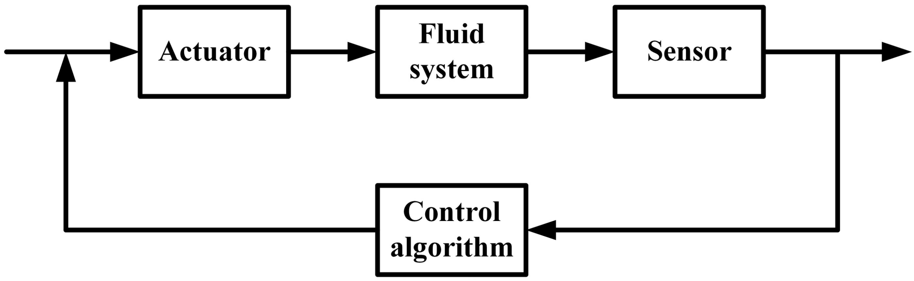

Figure 1.2 Schematic of the closed-loop control algorithm.

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.

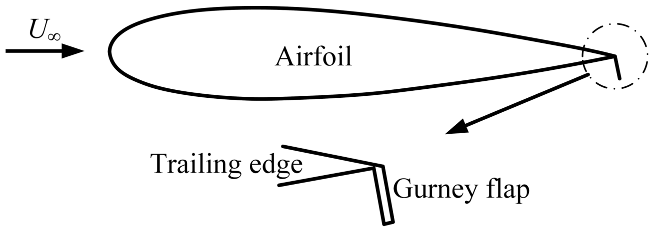

Figure 1.3 Schematic of a Gurney flap mounted on the pressure surface of an airfoil.

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).

https://doi.org/10.1017/9781316676448.002 Published online by Cambridge University Press

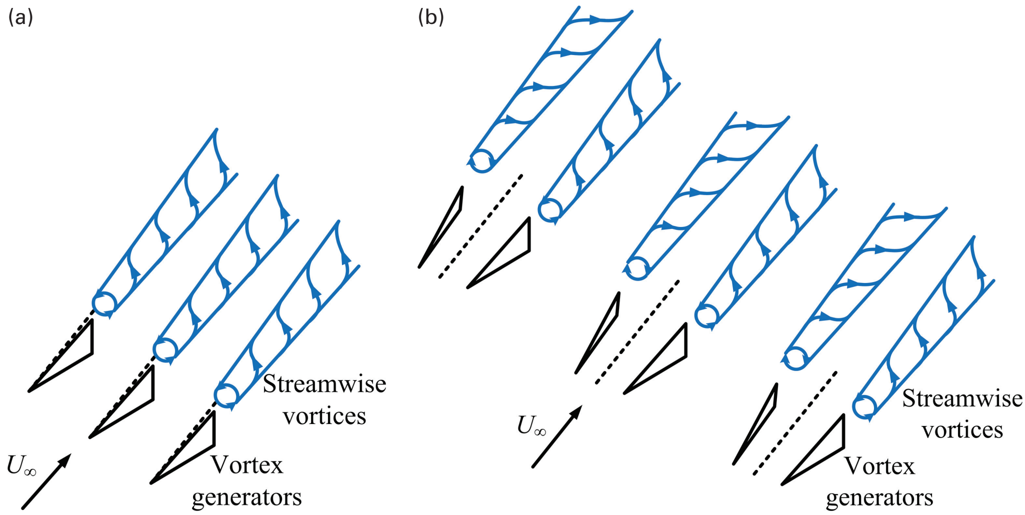

Figure 1.4 Schematic of vortex generators. (a) Co-rotating arrangement; (b) counter-rotating arrangement.

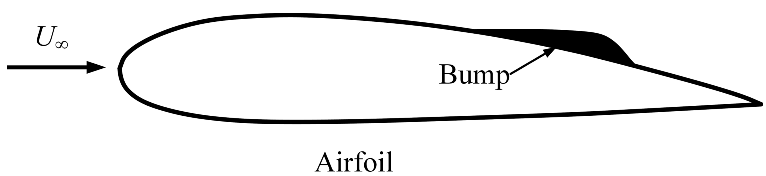

Figure 1.5 Schematic of an airfoil with a bump.

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

https://doi.org/10.1017/9781316676448.002 Published online by Cambridge University Press

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

https://doi.org/10.1017/9781316676448.002 Published online by Cambridge University Press

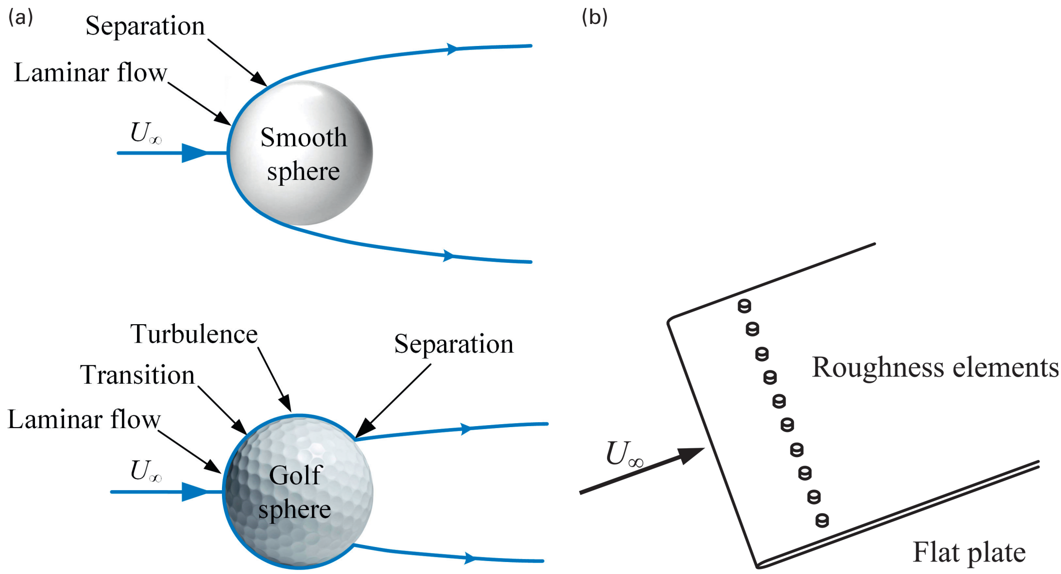

Figure 1.7 (a) Effect of dimples on a sphere. (b) Schematic of roughness elements placed on a flat plate.

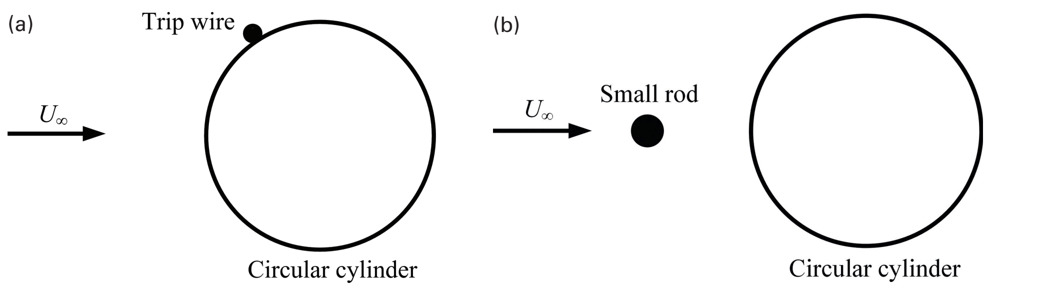

Figure 1.8 Schematic of a circular cylinder with a trip wire (a) and a small rod in the upstream position (b).

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

https://doi.org/10.1017/9781316676448.002 Published online by Cambridge University Press

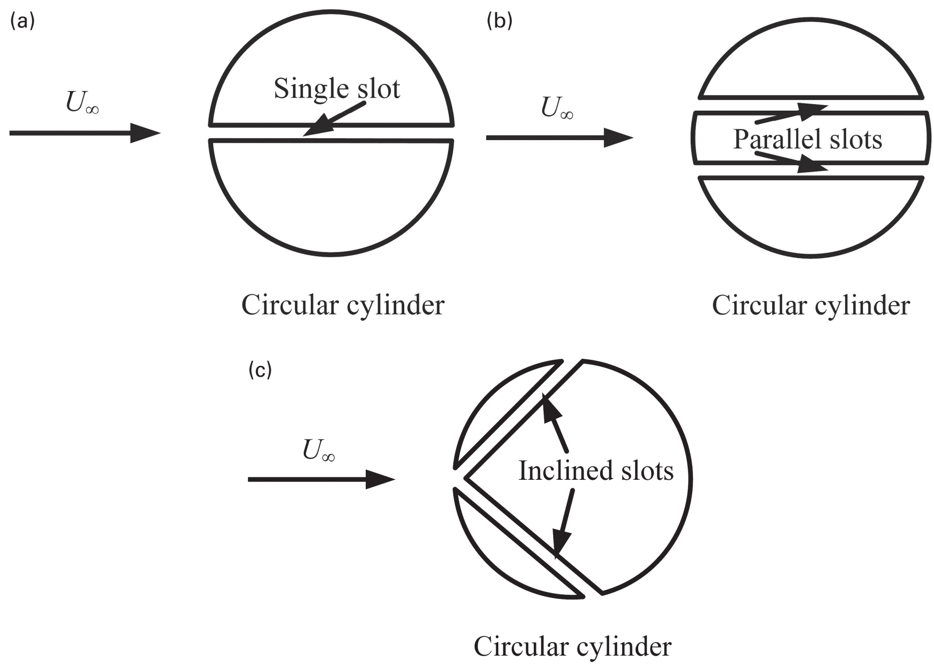

Figure 1.9 Schematic of a circular cylinder with bleed control. (a) One slot across the front and rear stagnations points; (b) two parallel slots; and (c) two inclined slots.

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.

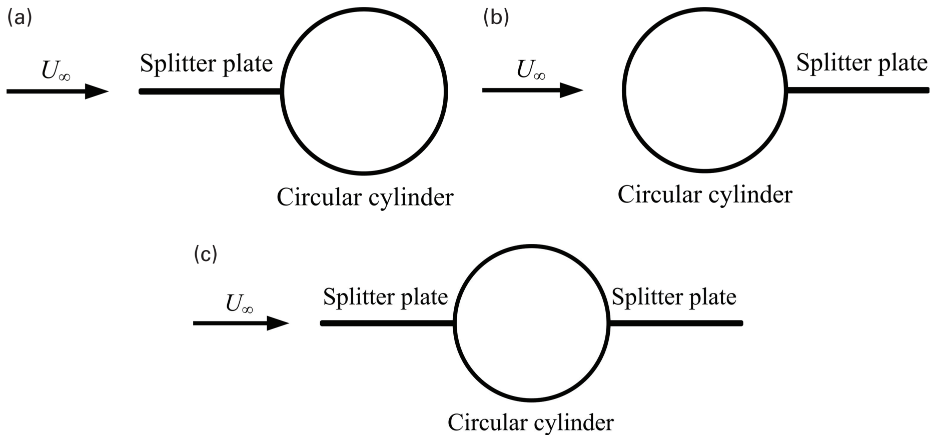

Figure 1.10 Schematic of a circular cylinder with splitter plates. (a) A splitter plate placed at upstream position; (b) a splitter plate placed at downstream position; and (c) two splitter plates placed at both upstream and downstream positions.

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

https://doi.org/10.1017/9781316676448.002 Published online by Cambridge University Press

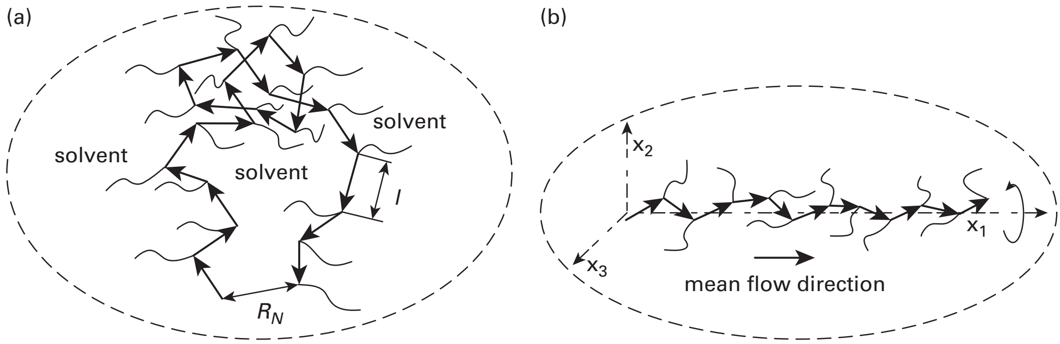

Figure 1.11 Schematic of polymer in solution at equilibrium (a) and its response to stretching by turbulent motions (b) (Jovanović et al. 2006). Reproduced with permission of The American Society of Mechanical Engineers.

for potential applications in engineering, such as oil transportation, heating and cooling systems, etc.

1.3.10 Biomimetic Techniques

Some specific features on organisms are shown in Figure 1.12. They might be related to high aerodynamic performance, and some biomimetic flow control techniques are proposed accordingly.

One can observe the deflection of the wing tip of a bird during its cruise stage (Figure 1.12(a)) and the raising of a bird's feathers during its landing (Figure 1.12(b)), which are considered to be the reason why birds can improve their aerodynamic performance. It has been found that the wing tip could reduce the lift-induced drag of the aircraft, which has been widely used in modern airplanes as a well-developed flow control technique. On the other hand, researchers have proved the effects of hairy coating on bluff bodies and airfoils, confirming the function of raising feathers during bird landing.

The owl has a special structure of combed serrations at the leading edge of its feathers (Figure 1.12(c)), which are not observed in most other birds. The combed serrations are found to be of importance to reduce noise by functioning as a vortex generator to attach the flow on the wing suction surface. Thus, the owl has a great ability to fly silently. The leading-edge serration could be used as an effective control approach for noise reduction, as has been indicated by Ito (2009) and Narayanan et al. (2015), and reviewed by Choi et al. (2012).

Insect wings are usually not smooth but corrugated, as shown in Figure 1.12(d). The corrugation allows the insect wing to have the advantages of low mass, high stiffness, and low membrane stress (Meng and Sun 2013). Some researchers, such as Hu and Tamai (2008) and Barnes and Visbal (2013), have pointed out that a corrugation airfoil could have a larger lift coefficient at post stall angles of attack. Thus, the corrugation configuration could be used as an approach to improve the aerodynamic performance of micro air vehicles (MAVs).

https://doi.org/10.1017/9781316676448.002 Published online by Cambridge University Press

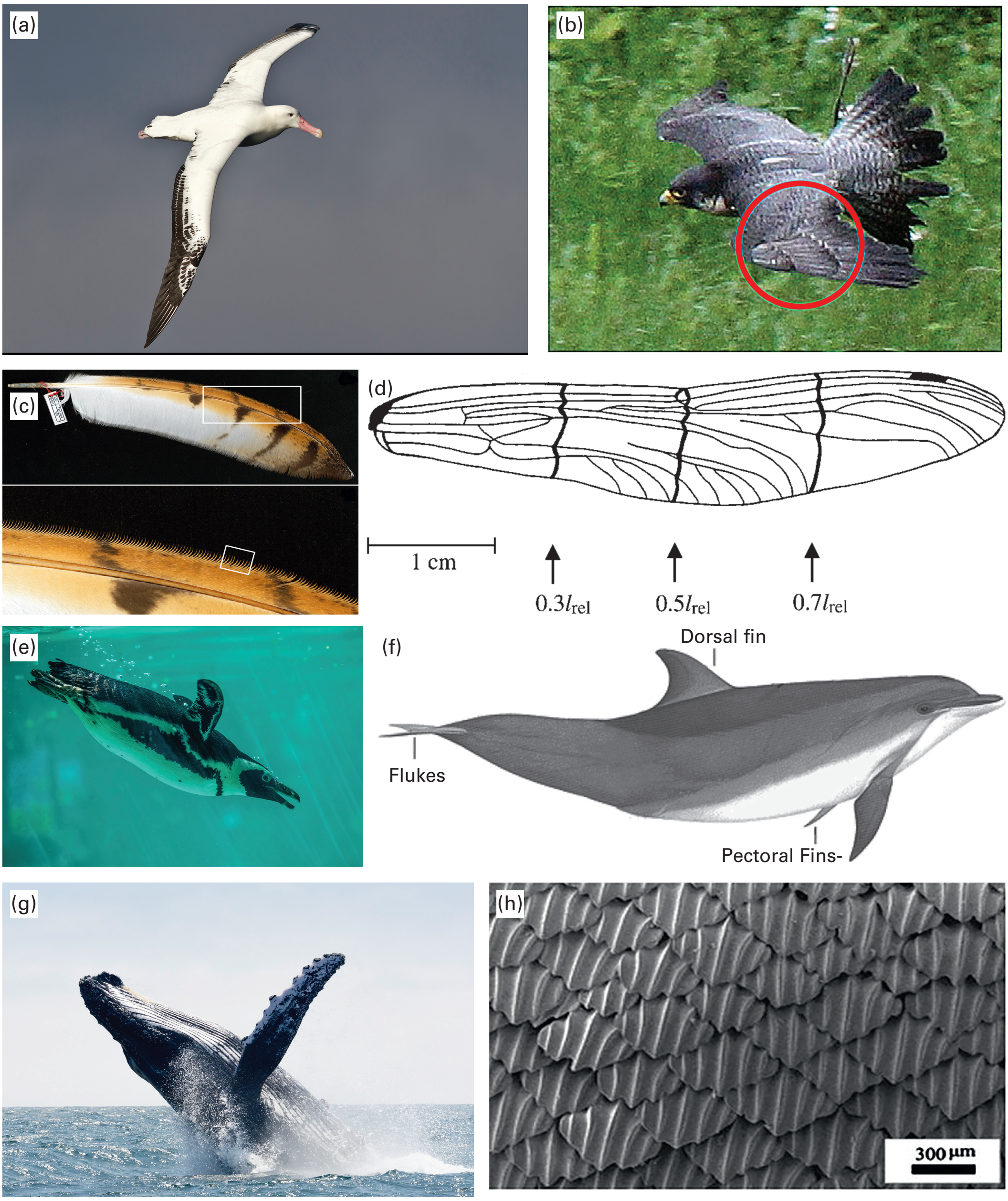

Figure 1.12 Some specific features on organisms that might be related to high aerodynamic performance. (a) Wing tip of an albatross. (b) Self-adaptive hairy flaps of a falcon (Brücker and Weidner 2014), reproduced with permission, copyright © 2014 Elsevier Ltd. All rights reserved. (c) Combed serrations on the leading edge of the owl feather (Bachmann and Wagner 2011), reproduced with permission from John Wiley and Sons. (d) Corrugation of a dragonfly forewing (Kesel 2000), reproduced with permission, copyright © The Company of Biologists Limited 2000. (e) Air bubbles releasing from a penguin. (f) Compliant skin of a dolphin (Allen and Bridges 2003), reproduced with permission, © John Wiley and Sons, 2003. (g) Tubercles on the leading edge of a humpback whale. (h) Riblet on sharkskin (Liu and Li 2012), reproduced with permission from Elsevier. (i) Riblets on a saguaro (Talley et al. 2001), reproduced with permission. (j) Water droplet sitting on the lotus leaf (upper) and micrographs of lotus leaf surface to show the microstructures (Bhushan and Jung 2011), reproduced with permission, copyright © 2011 Elsevier Ltd. All rights reserved.

https://doi.org/10.1017/9781316676448.002 Published online by Cambridge University Press

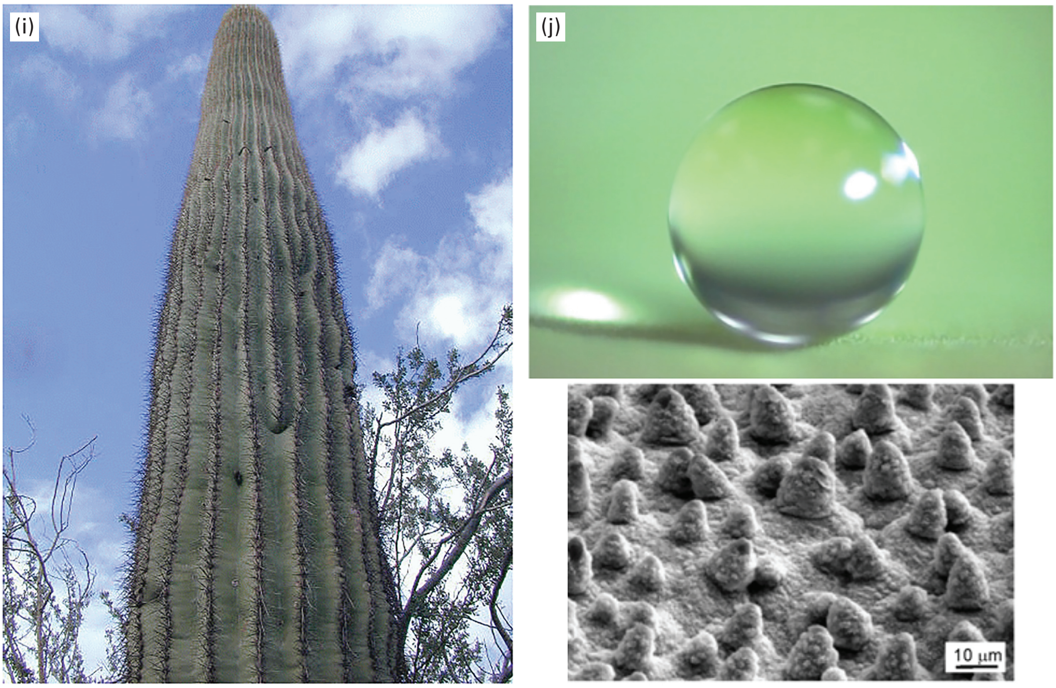

Figure 1.12 (*cont*).

A penguin may release air bubbles to reduce drag and thus promotes swimming speed (Figure 1.12(e)). Many researches, such as Xu et al. (2002), Elbing et al. (2008), and Jacob et al. (2010), have indicated that the air bubbles injected to the boundary layer could lead to a reduction in the friction drag. Thus, the air bubbles show great potential application for drag reduction in underwater vehicles, such as submarines.

It is found that the skin of a dolphin is compliant (Figure 1.12(f)), which is suggested to be effective in reducing the drag of the dolphin when swimming. Accordingly, a flow control technique, namely compliant coating, has been proposed. There have been many researches to show that compliant coating is capable of substantially delaying laminar-to -turbulence transition and reducing turbulent activities in the turbulent boundary layer. For reviews of this field please refer to Riley et al. (1988) and Gad-el-Hak (2002).

The leading edge of the flippers of humpback whales is also not smooth and has bumpy tubercles (Figure 1.12(g)). Experimental and numerical studies have suggested that the leading-edge tubercles are beneficial for aerodynamic performance at high angles of attack. A recent review on this field has been made by Aftab et al. (2016).

From a close-view, we can see that the sharkskin is comprised of small riblet structures (Figure 1.12(h)), which might be related to the drag reduction of shark swimming. Thus, riblets have been used as a useful drag reduction technique in the past, such as in the so-called sharkskin swimsuit.

Similarly, riblets also occur on one kind of saguaro with typical diameter of the order of 0.5 m and height of 10 m (Figure 1.12(i)). It is suggested that riblets are related to

https://doi.org/10.1017/9781316676448.002 Published online by Cambridge University Press

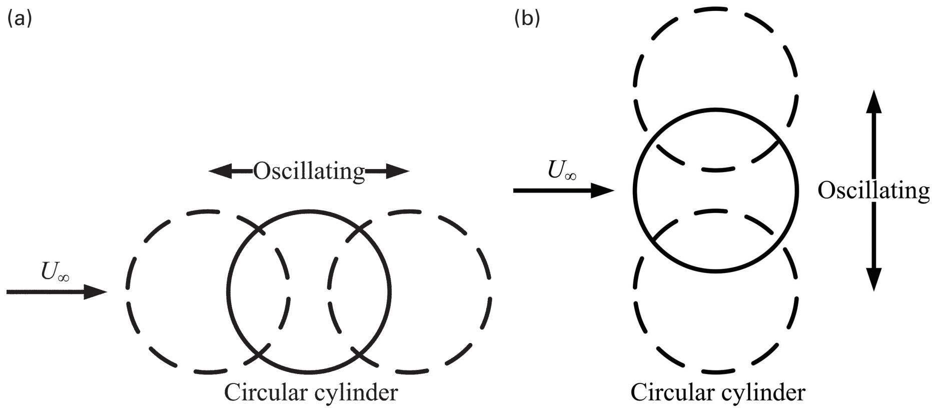

Figure 1.13 Schematic of a circular cylinder oscillating in the streamwise (a) and vertical (b) directions.

suppression of vortex-induced-vibration, which is beneficial for the saguaro in living up to 150 years of age with high wind velocity in their natural habitat.

It is well known that a water drop has a high static contact angle on the lotus leaf, as shown in Figure 1.12(j). The micrograph shows that the lotus leaf surface is very rough with microstructures, which are formed by papillose epidermal cells covered with epicuticular wax tubules. Such features enable the lotus leaf to self-clean and have low adhesion. Thus, the control idea of superhydrophobic surface is developed, where the artificial surface can be made by microstructures. It has been shown that the superhydrophobic surface could lead to a significant reduction in friction drag for both laminar (such as Busse et al. 2013) and turbulent (such as Daniello et al. 2009) flows. More details to show the effects can be found in the review papers by Rothstein (2010) and Bhushan and Jung (2011).

1.4 Active Flow Control

1.4.1 Oscillation and Flow Perturbation

Oscillation and perturbation in flow are two control approaches that may result in similar effects, that are usually imposed on bluff bodies and airfoils. The oscillation is achieved by forcing the controlled body to move in the streamwise (Figure 1.13(a)) or vertical (Figure 1.13(b)) direction. Similarly, the perturbations imposed in the flow could also be in the streamwise (Figure 1.14(a)) or vertical (Figure 1.14(b)) direction. Some primary conclusions have been made for the flow around an oscillating cylinder or the perturbed flow around a stationary cylinder, as has been summarized by Feng and Wang (2010, 2014).

First, vortex-synchronization could be induced by both methods, where the vortex shedding frequency is closely related to the excitation frequency. It could be categorized into two groups: vortex synchronization at the excitation frequency and at the subharmonic excitation frequency. Vertical oscillation and vertical flow perturbation may result

https://doi.org/10.1017/9781316676448.002 Published online by Cambridge University Press

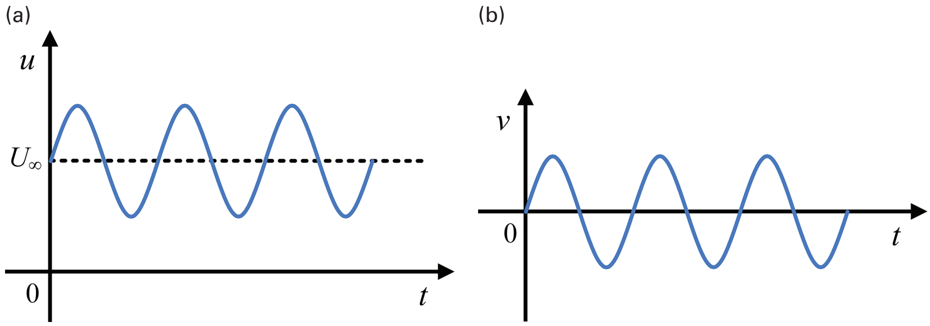

Figure 1.14 Schematic of flow perturbation in the streamwise (a) and vertical (b) directions.

in vortex synchronization at the excitation frequency, while streamwise oscillation and streamwise flow perturbation usually result in vortex synchronization at the subharmonic excitation frequency.

Second, the vortex-synchronization regime is related to both the excitation frequency and amplitude. The fundamental trend is that a higher excitation amplitude can induce a much larger vortex-synchronization regime. The vortex-synchronization regime induced by vertical oscillation and vertical flow perturbation is usually around the natural frequency, while that for the streamwise cases is usually around twice of the natural frequency.

Thirdly, the near wake dynamics could be modified by oscillation and flow perturbation. In particular, the symmetric vortex shedding mode could be induced by symmetric excitation, such as streamwise oscillation and streamwise flow perturbation.

Similar to the oscillation approach, rotation is another control method for the bluff body, as has been studied by Navrose et al. (2015). The oscillation method can also be used with a flat plate to control the boundary layer, where the drag could be reduced by up to 45%, as indicated by Choi (2002). Similarly, flexible wall oscillation is another approach for boundary layer control, as conducted by Shen et al. (2003).

1.4.2 Acoustic Excitation

Acoustic excitation is a control method based on a sound wave, which could be achieved by a loudspeaker, as shown in Figure 1.15. The basis for such control is the boundary layer receptivity. The acoustic pressure wave interacts with the boundary layer/shear layer and triggers the instability which results in global variations of the flow field. There have been studies to show that the acoustic excitation could increase both the lift and lift-to-drag ratio of the airfoil in the close and post stall regions (such as Yarusevych et al. 2007; Yang and Spedding 2013). In addition, the effects of acoustic excitation on the flow around circular cylinders (such as Mohany and Ziada 2009) and on the development of vortical structures (such as Leblanc 2001) and jets (such as Huang et al. 2013) have also been found. The sound press level, excitation frequency, as well as the Reynolds number, determine the effects. However, the experimental conditions, such as the test-section geometry and acoustic resonance, are also of great importance in achieving the ideal effects.

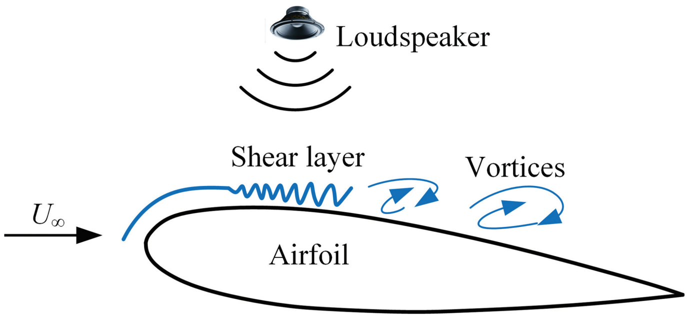

Figure 1.15 Schematic of flow around an airfoil under acoustic excitation.

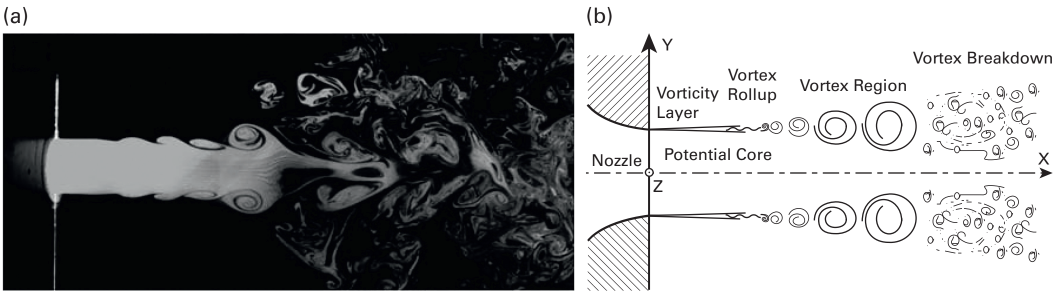

Figure 1.16 (a) Flow pattern of a jet at $Re_j = 1620$. (b) Schematic of a jet issuing from a nozzle (Todde et al. 2009), reproduced with permission, copyright © Springer 2009.

1.4.3 Jet

The jet, also known as free jet, steady jet or continuous jet, is one of the earliest techniques used for boundary layer flow control. When fluids are issuing from an orifice, flow separates from the edges to form a separated shear layer, which gradually rolls up into vortical structures, as shown in Figure 1.16. The vortices are undergoing flow transition as convecting downstream, resulting in the turbulent flow. The jet can enhance momentum mixing between inner and outer boundary layers, which is beneficial for separation delay. Similarly, suction control is another approach by drawing the low momentum fluids away from the near-wall region. Both blowing and suction can be used for flow control in various fields.

1.4.4 Synthetic Jet

The synthetic jet has been widely investigated since the 1990s. A typical synthetic jet actuator includes a cavity, an orifice and an oscillating device, such as a piezoceramic diaphragm or piston, as shown in Figure 1.17. An excitation signal drives the diaphragm or piston to move forward to and backward from the orifice, and thus the fluids are ejected from the orifice and sucked into the cavity, periodically. During the blowing cycle, the separated shear layer formed from the orifice edge grows and develops into

https://doi.org/10.1017/9781316676448.002 Published online by Cambridge University Press

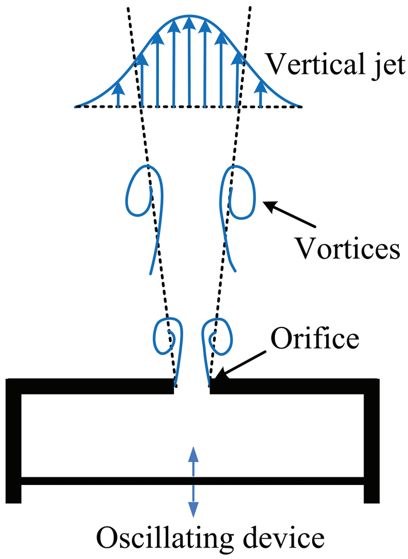

Figure 1.17 Schematic of a synthetic jet actuator.

vortical structures that are convecting downstream gradually due to the self-induced velocity. During the suction cycle, the vortical structures formed during the previous blowing cycles have moved further downstream and they are hardly influenced by the suction process. Thus, a series of vortical structures are formed periodically during the blowing and suction processes, which could enhance momentum mixing efficiency. The synthetic jet is also called the zero-net-mass-flux jet, as the net flow flux during one period is zero though the net momentum flux is not zero. The synthetic jet has become one of the most important active flow control techniques, and it has shown significant effects in various fields, as have been reviewed by Glezer and Amitay (2002), Luo and Xia (2005), and Zhang et al. (2008).

1.4.5 Plasma Actuator

Wide investigation of the plasma actuator for flow control started in the 1990s. The dielectric barrier discharge (DBD) plasma actuator is representative, though several other types have been developed, such as corona discharge actuator and plasma spark-jet actuator. A typical DBD plasma actuator consists of an exposed electrode and an embedded electrode, separated by a dielectric sheet, as shown in Figure 1.18. When the electrodes are supplied with high voltage and frequency, the air over the embedded electrode is ionized and thus a wall jet forms. Accompanying the wall jet, the flow separates from the wall and rolls up into a vortex. These are the two main features of the DBD plasma actuator: inducing a wall jet and a starting vortex. The advantages of plasma control include electronic design with no moving parts, extremely fast response and real-time control ability, low power consumption, low mass, and simple to use, making the plasma actuator one of the most popoular techniques for

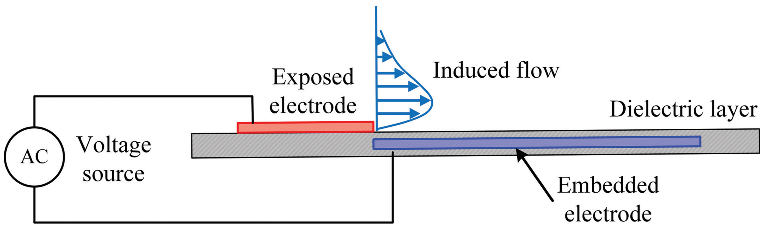

Figure 1.18 Schematic of a DBD plasma actuator.

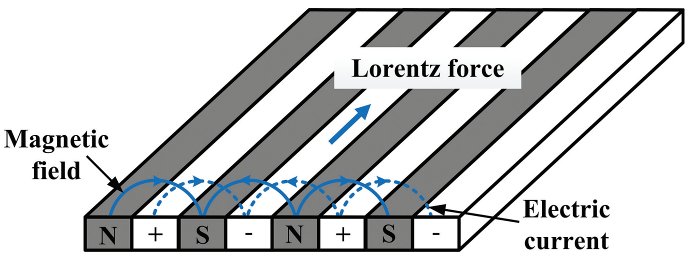

Figure 1.19 Schematic of an arrangement for the creation of the Lorentz force (Adapted from Berger et al. 2000). Reproduced with permission from AIP Publishing.

flow control applications. The main developments can also be found in the review papers by Moreau (2007), Corke et al. (2010), Wang et al. (2013a), Wu and Li (2015).

1.4.6 Lorentz Force

The subject of flow control with Lorentz force (or electromagnetic body force) originates from electromagnetism. When a charged particle is moving in the presence of an electric field and a magnetic field, it will experience a Lorentz force. The Lorentz force required for flow control can be created by placing electrodes and magnets side by side, parallel to one another, as shown in Figure 1.19. The direction of the Lorentz force can be changed by varying the direction of either electric field or magnetic field, and its magnitude can be adjusted by varying the strength of either electric or magnetic field. Thus, the Lorentz force could be produced in a sinusoidal waveform and in either spanwise or streamwise direction relative to the free stream. The spanwise Lorentz force could reduce the friction drag of the turbulent boundary layer, though the streamwise Lorentz force may increase it. Moreover, the Lorentz force could reduce flow separation and thus increase the lift coefficient while reducing the drag coefficient of airfoils.

1.5 Concluding Remarks

Flow control attempts to introduce perturbations into the flow field to alter the original flow development path into an ideal state, and thus to achieve the desired

https://doi.org/10.1017/9781316676448.002 Published online by Cambridge University Press

goals, such as lift enhancement, drag reduction, vibration suppression, noise reduction, fuel and heat transfer enhancement, etc. It is of great significance for not only the development of the subject of fluid mechanics but also has great potential applications in engineering. Thus, flow control has attracted much attention. A book about flow control is also very useful for postgraduate students, researchers and engineers.

This book introduces most of the important and typical flow control techniques, including the most recent developments. It firstly introduces most of passive and active flow control techniques briefly in this introduction chapter. Then, the main content of the book follows different kinds of flow control techniques. Each chapter will mainly discuss one typical control method, including its fundamental characteristics, applications in various fields, and control mechanisms. In this way, it is expected that the readers will be able to better understand and master flow control.

References

Aftab, S. M. A., Razak, N. A., Rafie, A. S. M., and Ahmad, K. A. Mimicking the humpback whale: an aerodynamic perspective. *Progress in Aerospace Sciences*, 2016, 84: 48–69

Akilli, H., Sahin, B., and Tumen, N. F. Suppression of vortex shedding of circular cylinder in shallow water by a splitter plate. *Flow Measurement and Instrumentation*, 2005, 16(4): 211–219

Allen, L. and Bridges, T. J. Flow past a swept wing with a compliant surface: stabilizing the attachment-line boundary layer. *Studies in Applied Mathematics*, 2003, 110(4): 333–349

Report of the Group of Personalities formed by Busquin P. European Aeronautics: A Vision for 2020. Published by the European Commission, 2001

Aydin, B. T., Cetiner, O., and Unal, M. F. Effect of self-issuing jets along the span on the near-wake of a square cylinder. *Experiments in Fluids*, 2010, 48(6): 1081–1094

Bachmann, T. and Wagner, H. The three-dimensional shape of serrations at barn owl wings: towards a typical natural serration as a role model for biomimetic applications. *Journal of Anatomy*, 2011, 219(2): 192–202

Baek, H. and Karniadakis, G. E. Suppressing vortex-induced vibrations via passive means. *Journal of Fluids and Structures*, 2009, 25(5): 848–866

Barnes, C. J. and Visbal, M. R. Numerical exploration of the origin of aerodynamic enhancements in low-Reynolds number corrugated airfoils. *Physics of Fluids*, 2013, 25(11): 115106

Berger, T. W., Kim, J., Lee, C., and Lim, J. Turbulent boundary layer control utilizing the Lorentz force. *Physics of Fluids*, 2000, 12(3): 631–649

Bhushan, B. and Jung, Y. C. Natural and biomimetic artificial surfaces for super hydrophobicity, self-cleaning, low adhesion, and drag reduction. *Progress in Materials Science*, 2011, 56(1): 1–108

Brücker, C. and Weidner, C. Influence of self-adaptive hairy flaps on the stall delay of an airfoil in ramp-up motion. *Journal of Fluids and Structures*, 2014, 47: 31–40

Busse, A., Sandham, N. D., McHale, G., and Newton, M. I. Change in drag, apparent slip and optimum air layer thickness for laminar flow over an idealised superhydrophobic surface. *Journal of Fluid Mechanics*, 2013, 727: 488–508

Celik, B., Akdag, U., Gunes, S., and Beskok, A. Flow past an oscillating circular cylinder in a channel with an upstream splitter plate. *Physics of Fluids*, 2008, 20(10): 103603

Chen, Y. C., Liu, H., Zhang, B. Q., and Zhu, Z. Q. A review on drag reduction study and application for large aircraft. *The Application and Development of CFD in Large Civil Aircraft*, Shanghai Jiao Tong University Press, 2009, 32–47 (in Chinese)

Choi, K. S. Near-wall structure of turbulent boundary layer with spanwise-wall oscillation. *Physics of Fluids*, 2002, 14(7): 2530–2542

Choi, H., Park, H., Sagong, W., and Lee, S. Biomimetic flow control based on morphological features of living creaturesa. *Physics of Fluids*, 2012, 24(12): 121302

Corke, T. C., Enloe, C. L., and Wilkinson, S. P. Dielectric barrier discharge plasma actuators for flow control. *Annual Review of Fluid Mechanics*, 2010, 42: 505–529

Daniello, R. J., Waterhouse, N. E., and Rothstein, J. P. Drag reduction in turbulent flows over superhydrophobic surfaces. *Physics of Fluids*, 2009, 21(8): 085103

Ekmekci, A. and Rockwell, D. Effects of a geometrical surface disturbance on flow past a circular cylinder: a large-scale spanwise wire. *Journal of Fluid Mechanics*, 2010, 665: 120–157

Elbing, B. R., Winkel, E. S., Lay, K. A., Ceccio, S. L., Dowling, D. R., and Perlin, M. Bubble-induced skin-friction drag reduction and the abrupt transition to air-layer drag reduction. *Journal of Fluid Mechanics*, 2008, 612: 201–236

Feng, L. H. and Wang, J. J. Circular cylinder vortex-synchronization control with a synthetic jet positioned at the rear stagnation point. *Journal of Fluid Mechanics*, 2010, 662: 232–259

Feng, L. H. and Wang, J. J. Modification of a circular cylinder wake with synthetic jet: Vortex shedding modes and mechanism. *European Journal of Mechanics-B/Fluids*, 2014, 43: 14–32

Fransson, J. H. M., Talamelli, A., Brandt, L., and Cossu, C. Delaying transition to turbulence by a passive mechanism. *Physical Review Letters*, 2006, 96(6): 064501

Fu, H. and Rockwell, D. Shallow flow past a cylinder: control of the near wake. *Journal of Fluid Mechanics*, 2005, 539: 1–24

Gad-el-Hak, M. Compliant coatings for drag reduction. *Progress in Aerospace Sciences*, 2002, 38 (1): 77–99

Garner, P. L., Meredith, P. T., and Stoner, R. C. Areas for future CFD development as illustrated by transport aircraft applications. AIAA Paper 1991–1527

Glezer, A. and Amitay, M. Synthetic jets. *Annual Review of Fluid Mechanics*, 2002, 34: 503–529

Hu, H. and Tamai, M. Bioinspired corrugated airfoil at low Reynolds numbers. *Journal of Aircraft*, 2008, 45(6): 2068–2077

Huang, R. F., Jufar, S. R., and Hsu, C. M. Flow and mixing characteristics of swirling double-concentric jets subject to acoustic excitation. *Experiments in Fluids*, 2013, 54(1): 1421

Hwang, J. Y., Yang, K. S., and Sun, S. H. Reduction of flow-induced forces on circular cylinder using a detached splitter plate. *Physics of Fluids*, 2003, 15(8): 2433–2436

Hwang, J. Y. and Yang, K. S. Drag reduction on a circular cylinder using dual detached splitter plates. *Journal of Wind Engineering and Industrial Aerodynamics*, 2007, 95(7): 551–564

Iollo, A. and Zannetti, L. Trapped vortex optimal control by suction and blowing at the wall. *European Journal of Mechanics-B/Fluids*, 2001, 20(1): 7–24

Ito, S. Aerodynamic influence of leading-edge serrations on an airfoil in a low Reynolds number – a study of an owl wing with leading edge serrations. *Journal of Biomechanical Science and Engineering*, 2009, 4(1): 117–123

Jacob, B., Olivieri, A., Miozzi, M., Campana, E. F., and Piva, R. Drag reduction by microbubbles in a turbulent boundary layer. *Physics of Fluids*, 2010, 22(11): 115104.

Jimenez, J. Turbulent flows over rough walls. *Annual Review of Fluid Mechanics*, 2004, 36: 173–196

Joslin, R. D. and Miller, D. N. Fundamentals and applications of modern flow control. American Institute of Aeronautics and Astronautics, 2009

Jovanović, J., Pashtrapanska, M., Frohnapfel, B., Durst, F. K. J., and Koskinen, K. On the mechanism responsible for turbulent drag reduction by dilute addition of high polymers: theory, experiments, simulations, and predictions. *Journal of Fluids Engineering*, 2006, 128(1): 118–130

Kesel, A. B. Aerodynamic characteristics of dragonfly wing sections compared with technical aerofoils. *Journal of Experimental Biology*, 2000, 203(20): 3125–3135

Lasagna, D., Donelli, R., De Gregorio, F., and Luso, G. Effects of a trapped vortex cell on a thick wing airfoil. *Experiments in Fluids*, 2011, 51(5): 1369–1384

Leblanc, S. Acoustic excitation of vortex instabilities. *Physics of Fluids*, 2001, 13(11): 3496–3499

Li, P.F., Zhang, B. Q., Chen, Y. C., and Chen, Z. L. Wave drag reduction of airfoil with shock control bump. *Acta Aeronautica et Astronautica Sinica*, 2011, 32(6): 971–977 (in Chinese)

Lin, J. C. Review of research on low-profile vortex generators to control boundary-layer separation. *Progress in Aerospace Sciences*, 2002, 38(4): 389–420

Liu, Y. and Li, G. A new method for producing "Lotus Effect" on a biomimetic shark skin. *Journal of Colloid and Interface Science*, 2012, 388(1): 235–242

Lu, F. K., Li, Q., and Liu, C. Microvortex generators in high-speed flow. *Progress in Aerospace Sciences*, 2012, 53: 30–45

Luo, Z. B. and Xia, Z. X. Advances in synthetic jet technology and applications in flow control. *Advances in Mechanics*, 2005, 35(2): 221–234

Ma, H. D. and Cui, E. J. Drag prediction and reduction for civil transportation. *Mechanics in Engineering*. 2007, 29(2): 1–8

Meng. X. G. and Sun, M. Aerodynamic effects of wing corrugation at gliding flight at low Reynolds numbers. *Physics of Fluids*, 2013, 25(7): 071905

Milholen, W. E. and Owens, L. R. On the application of contour bumps for transonic drag reduction. AIAA Paper 2005–462

Mohany, A. and Ziada, S. Effect of acoustic resonance on the dynamic lift forces acting on two tandem cylinders in cross-flow. *Journal of Fluids and Structures*, 2009, 25(3): 461–478

Moreau, E. Airflow control by non-thermal plasma actuators. *Journal of Physics D: Applied Physics*, 2007, 40(3): 605–636

Steering Committee for the Decadal Survey of Civil Aeronautics, National Research Council. *Decadal Survey of Civil Aeronautics: Foundation for the Future*. Published by the National Academies Press, 2006

Narayanan, S., Chaitanya, P., Haeri, S., Joseph, P., Kim, J. W., and Polacsek, C. Airfoil noise reductions through leading edge serrations. *Physics of Fluids*, 2015, 27(2): 025109

Navrose, Meena, J. and Mittal, S. Three-dimensional flow past a rotating cylinder. *Journal of Fluid Mechanics*, 2015, 766: 28–53

Olsman, W. F. and Colonius, T. Numerical simulation of flow over an airfoil with a cavity. *AIAA Journal*, 2011, 49(1): 143–149

Olsman, W. F., Willems, J. F., Hirschberg, A., Colonius, T., and Trieling, R. R. Flow around a NACA0018 airfoil with a cavity and its dynamical response to acoustic forcing. *Experiments in Fluids*, 2011, 51(2): 493–509

Procaccia, I., L'vov, V. S., and Benzi, R. Colloquium: Theory of drag reduction by polymers in wall-bounded turbulence. *Reviews of Modern Physics*, 2008, 80(1): 225–247

Riley, J. J., Gad-El-Hak, M., and Metcalfe, R. W. Compliant coatings. *Annual Review of Fluid Mechanics*, 1988, 20: 393–420

Rothstein, J. P. Slip on superhydrophobic surfaces. *Annual Review of Fluid Mechanics*, 2010, 42: 89–109

Serson, D., Meneghini, J. R., Carmo, B. S., Volpe, E. V., and Gioria, R. S. Wake transition in the flow around a circular cylinder with a splitter plate. *Journal of Fluid Mechanics*, 2014, 755: 582–602

Shen, L., Zhang, X., Yue, D. K., and Triantafyllou, M. S. Turbulent flow over a flexible wall undergoing a streamwise travelling wave motion. *Journal of Fluid Mechanics*, 2003, 484: 197–221

Shi, X. D. and Feng, L. H. Control of flow around a circular cylinder by bleed near the separation points. *Experiments in Fluids*, 2015, 56(12): 214

Son, K., Choi, J., Jeon, W.P., and Choi, H. Mechanism of drag reduction by a surface trip wire on a sphere. *Journal of Fluid Mechanics*, 2011, 672: 411–427

Talley, S., Iaccarino, G., Mungal, G., and Mansour, N. An experimental and computational investigation of flow past cacti. Annual Research Briefs. Center for Turbulence Research, NASA Ames/Stanford University, 2001: 51–63

Tian, Y., Liu, P., and Peng, J. Using shock control bump to improve transonic buffet boundary of airfoil. *Acta Aeronautica et Astronautica Sinica*, 2011, 32(8): 1421–1428 (in Chinese)

Todde, V., Spazzini, P. G., and Sandberg, M. Experimental analysis of low-Reynolds number free jets. *Experiments in Fluids*, 2009, 47(2): 279–294

Wang, J. J., Li, Y. C., and Choi, K. S. Gurney flap – Lift enhancement, mechanisms and applications. *Progress in Aerospace Sciences*, 2008, 44(1): 22–47

Wang, J. J., Zhang, P. F., Lu, S. F., and Wu, K. Drag reduction of a circular cylinder using an upstream rod. *Flow, Turbulence and Combustion*, 2006, 76(1): 83–101

Wang, J. J., Choi, K. S., Feng, L. H., Jukes, T.N., and Whalley, R. D. Recent developments in DBD plasma flow control. *Progress in Aerospace Sciences*, 2013a, 62: 52–78

Wang, J. J., Pan, C., Choi, K. S., Gao, L., and Lian, Q. X. Formation, growth and instability of vortex pairs in an axisymmetric stagnation flow. *Journal of Fluid Mechanics*, 2013b, 725: 681–708

Washburn, A. E., Gorton, S. A., and Anders, S. G. Snapshot of active flow control research at NASA Langley. AIAA Paper 2002–3155

Wu, Y. and Li, Y. Progress and outlook of plasma flow control. *ACTA Aeronautica et Astronautica Sinica*, 2015, 36: 381–405 (in Chinese)

Xu, J., Maxey, M. R., and Karniadakis, G. E. Numerical simulation of turbulent drag reduction using micro-bubbles. *Journal of Fluid Mechanics*, 2002, 468: 271–281

Yang, S. L. and Spedding, G. R. Separation control by external acoustic excitation at low Reynolds numbers. *AIAA Journal*, 2013, 51(6): 1506–1515

Yarusevych, S., Sullivan, P. E., and Kawall, J. G. Effect of acoustic excitation amplitude on airfoil boundary layer and wake development. *AIAA Journal*, 2007, 45(4): 760–771

Zhang, P. F., Wang, J. J., and Feng, L. H. Review of zero-net-mass-flux jet and its application in separation flow control. *Science in China Series E: Technological Sciences*, 2008, 51(9): 1315–1344

Zhang, P. F., Wang, J. J., and Huang, L. X. Numerical simulation of flow around cylinder with an upstream rod in tandem at low Reynolds numbers. *Applied Ocean Research*, 2006a, 28(3): 183–192

Zhang, P. F., Wang, J. J., Lu, S. F., and Mi, J. Aerodynamic characteristics of a square cylinder with a rod in a staggered arrangement. *Experiments in Fluids*, 2005, 38(4): 494–502

Zhang, P., Gao, L., and Wang, J. J. Drag reduction of a disk with an upstream rod. *Wind and Structures*, 2006b, 9(3): 245–254