CHAPTER ONE

# Introduction

*Thinking is one of the greatest joys of humankind.*
*(Galileo Galilei, 1564–1642)*

*The farther backward you can look, the farther forward you are likely to see.*
*(Sir Winston Leonard Spencer Churchill, 1874–1965)*

## PROLOGUE

The subject of flow control is broadly introduced in this first chapter, leaving much of the details to the subsequent chapters of the book. The ability to manipulate a flowfield actively or passively to effect a desired change is of immense technological importance, and this undoubtedly accounts for the subject's being more hotly pursued by scientists and engineers than any other topic in fluid mechanics. The potential benefits of realizing efficient flow-control systems range from saving billions of dollars in annual fuel costs for land, air, and sea vehicles to achieving economically and environmentally more competitive industrial processes involving fluid flows. In this monograph both the classical tools and the more modern strategies of flow control are covered. Methods of control to achieve transition delay, separation postponement, lift enhancement, drag reduction, turbulence augmentation, and noise suppression are considered. The treatment is tutorial at times, which makes the material accessible to the graduate student in the field of fluid mechanics. Emphasis is placed on external boundary-layer flows, although applicability of some of the methods discussed for internal flows as well as free-shear flows will be mentioned. An attempt is made to present a unified view of the means by which different methods of control achieve a variety of end results. Performance penalties associated with a particular method such as cost, complexity, and trade-off will be elaborated upon throughout the book.

## 1.1 What Is Flow Control?

Before we get started it might be a good idea to explain what is meant by flow control. The topic, as discussed in this monograph, is not related to flow-rate control via manual or automatic valves. Rather it is the attempt to alter the character or disposition of a flowfield favorably that is of concern to us here. Many definitions for the topic exist, and some differentiate between (active) flow control and (passive) flow management. My favorite definition was offered by Flatt[1] in 1961 as applied to wall-bounded flows but could easily be extended to free-shear flows: "Boundary layer control includes any mechanism or process through which the boundary layer of a fluid flow is caused to behave differently than it normally would were the flow developing naturally along a smooth straight surface." Prandtl (1904) pioneered the modern use of flow control in his epoch-making presentation to the Third International Congress of Mathematicians held at Heidelberg, Germany. In just eight pages (as required for acceptance by the congress) of a paper titled *Über Flüssigkeitsbewegung bei sehr kleiner Reibung* (*On Fluid Motion with Very Small Friction*), Prandtl introduced the boundary-layer theory, explained the mechanics of steady separation, opened the way for understanding the motion of real fluids, and described several experiments in which the boundary layer was controlled.

Prandtl (1904) used active control of the boundary layer to show the great influence such a control exerted on the flow pattern. He used suction to delay boundary-layer separation from the surface of a cylinder. Notwithstanding Prandtl's success, aircraft designers in the three decades following his convincing demonstration were accepting lift and drag of airfoils as predestined characteristics with which no man could or should tamper (Lachmann 1961). This predicament changed mostly owing to the German research in boundary-layer control pursued vigorously shortly before and during the Second World War. In the two decades following the war, extensive research on laminar flow control, in which the boundary layer formed along the external surfaces of an aircraft is kept in the low-drag laminar state, was conducted in Europe and the United States, culminating in the successful flight-test program of the X-21 in which suction was used to delay transition on a swept wing up to a chord Reynolds number of $4.7 \times 10^7$. The oil crisis of the early 1970s brought renewed interest in novel methods of flow control to reduce skin-friction drag even in turbulent boundary layers. In the 1990s, the need to reduce the emissions of greenhouse gases and to construct supermaneuverable fighter planes, faster and quieter underwater vehicles, and hypersonic transport aircraft (e.g., the U.S. National Aerospace Plane) provided new challenges for researchers in the field of flow control.

The major goal of this monograph is to introduce the subject broadly, to present a unified view of the different control methods to achieve a variety of end results, and to provide an up-to-date view of the fundamentals of some basic flows and control practices. The number of journal articles and proceedings available on flow control is daunting. For example, a recent bibliography on the rather narrow sub-subject of skin-friction reduction by polymers and other additives cites over 4900 references (Nadolink and Haigh 1995). Therefore, citations in the present book will be rather selective—indeed very limited. To avoid having all 441 pages of this book as a gigantic list of references, numerous good articles will not be cited. At times, the treatment of the subject matter herein is pedagogical and is designed to attract newcomers to the field and to help the reader in navigating through the colossal literature available on flow-control fundamentals and practices. Emphasis is placed on the technologically important external boundary-layer flows, although applicability of some of

[1] All references are listed alphabetically in the bibliography at the end of the book.

the methods discussed for internal flows as well as free-shear flows will be covered as appropriate. The same vorticity considerations brilliantly employed by Lighthill (1963a) to place the boundary layer correctly in the flow as a whole are used to explain many of the flow-control techniques discussed in this book. The history of the subject is briefly and broadly recalled in the following section.

## 1.2 Five Eras of Flow Control

Flow control involves passive or active devices to effect a beneficial change in wall-bounded or free-shear flows. Whether the task is to delay or advance transition, to suppress or enhance turbulence, or to prevent or provoke separation, useful end results include drag reduction, lift enhancement, mixing augmentation, and flow-induced noise suppression. Broadly, there are perhaps five distinct eras in the development of the art and science of this challenging albeit very useful field of research and technology: the empirical era (prior to 1900), the scientific era (1900–1940), the World War II era (1940–1970), the energy crisis era (1970–1990), and the 1990s and beyond.

The art of flow control probably has its roots in prehistoric times when streamlined spears, sickle-shaped boomerangs, and fin-stabilized arrows evolved empirically (Williams 1987) by the sheer perseverance of archaic Homo sapiens who knew nothing about air resistance or aerodynamic principles. Three *aerodynamically correct* wooden spears were recently excavated in an open-pit coal mine near Hannover, Germany (Dennell 1997). Archaeologists dated the carving of those complete spears to about 400,000 years ago (Thieme 1997), which strongly suggests early Stone Age ancestors possessing resourcefulness and skills once thought to be characteristics that came only with fully modern Homo sapiens.

Modern man also artfully applied flow-control methods to achieve certain technological goals. Relatively soon after the dawn of civilization and the establishment of an agricultural way of life 8000 years ago, complex systems of irrigation were built along inhabited river valleys to control the waterflow, thus freeing man from the vagaries of the weather. Some resourceful albeit mischievous citizens of the Roman Empire discovered that adding the right kind of diffuser to the calibrated convergent nozzle ordinarily installed at home outlets of the public water main significantly increased the charge of potable water over that granted by the emperor. For centuries, farmers knew the value of windbreaks to keep topsoil in place and to protect fragile crops.

The science of flow control originated with Prandtl (1904), who introduced the boundary-layer theory, explained the physics of the separation phenomena, and described several experiments in which a boundary layer was controlled. Thus, the scientific method to control a flowfield, or the second era of flow control, was born. Slowly but surely, the choice of flow-control devices was no longer a trial and error feat, but physical reasoning and even first principles were more often than not used for rational design of such artifacts.

Stimulated by the Second World War and the subsequent Cold War, that trend accelerated significantly during the third era (1940–1970). Military needs of the superpowers dictated the development of fast, highly maneuverable, efficient aircraft, missiles, ships, submarines, and torpedoes, and flow control played a major role in achieving these goals. Natural laminar flow (in which shaping is used to delay transition), laminar flow control (in which nonpassive strategies are employed to keep the flow laminar), and polymer drag reduction were notable achievements during this era. Partial summaries of flow-control research during this period are presented in the books edited by Lachmann (1961) and Wells (1969).

The energy crises exemplified by the 1973 Arab oil embargo brought about a noticeable shift of interest from the military sector to the civilian one. During the period 1970–1990, government agencies and private corporations around the world, but particularly in the industrialized countries, invested valuable resources in the search for methods to conserve energy, and hence drag reduction for civilian air, sea, and land vehicles; for pipelines; and for other industrial devices was emphasized. The availability of fast, inexpensive computers made it possible to simulate numerically complex flow situations that had not been approachable analytically. Some control strategies, for example, transition-delaying compliant coatings (Gad-el-Hak 1996a), were rationally optimized using computational fluid dynamics. Large-eddy breakup devices (LEBUs) and riblets are examples of control methods developed during this period to reduce skin-friction drag in turbulent boundary layers. Good sources of information on these and other devices introduced during the fourth era are the books edited by Hough (1980); Bushnell and Hefner (1990); and Barnwell and Hussaini (1992). Numerous meetings devoted to flow control, particularly drag reduction, were held during this period. Plentiful fuel supplies during the 1990s and the typical short memory of the long gas lines during 1973 have, unfortunately, somewhat dulled the urgency and enthusiasm for energy conservation research as well as practice. Witness—at least in the United States—the awakening of the long-hibernated gas-guzzler automobile and the recent run on house-size sport utility vehicles, a.k.a. land barges.

For the 1990s and beyond, more complex reactive control devices geared specifically toward manipulating the omnipresent coherent structures in transitional and turbulent shear flows (Cantwell 1981; Robinson 1991) are being pursued by several researchers. Theoretical advances in chaos control and the development of microelectromechanical systems (MEMS) and neural networks should help such efforts. Articles specifically addressing reactive control strategies include those by Wilkinson (1990); Moin and Bewley (1994); and Gad-el-Hak (1994, 1996b). The MEMS are discussed in Chapter 13, and reactive flow control is emphasized in the last chapter of this book.

All five eras of flow control are seen from the perspective of the history of the universe timeline shown in Figure 1.1.

## 1.3 Has the Field Crested?

There are those who consider fluid mechanics to be a mature subject that led to very useful technological breakthroughs in the past but that the pace of improvements is fast reaching the point at which returns on investment in research are not sufficiently impressive. As we approach the twenty-first century, the skeptics claim, little new scientific or engineering breakthroughs are to be expected from the aging field of study. It may be worth remembering that much the same was said about physics toward the end of the nineteenth century. Self-satisfied that almost all experimental observations of the time could be fitted into either Newton's theory of mechanics

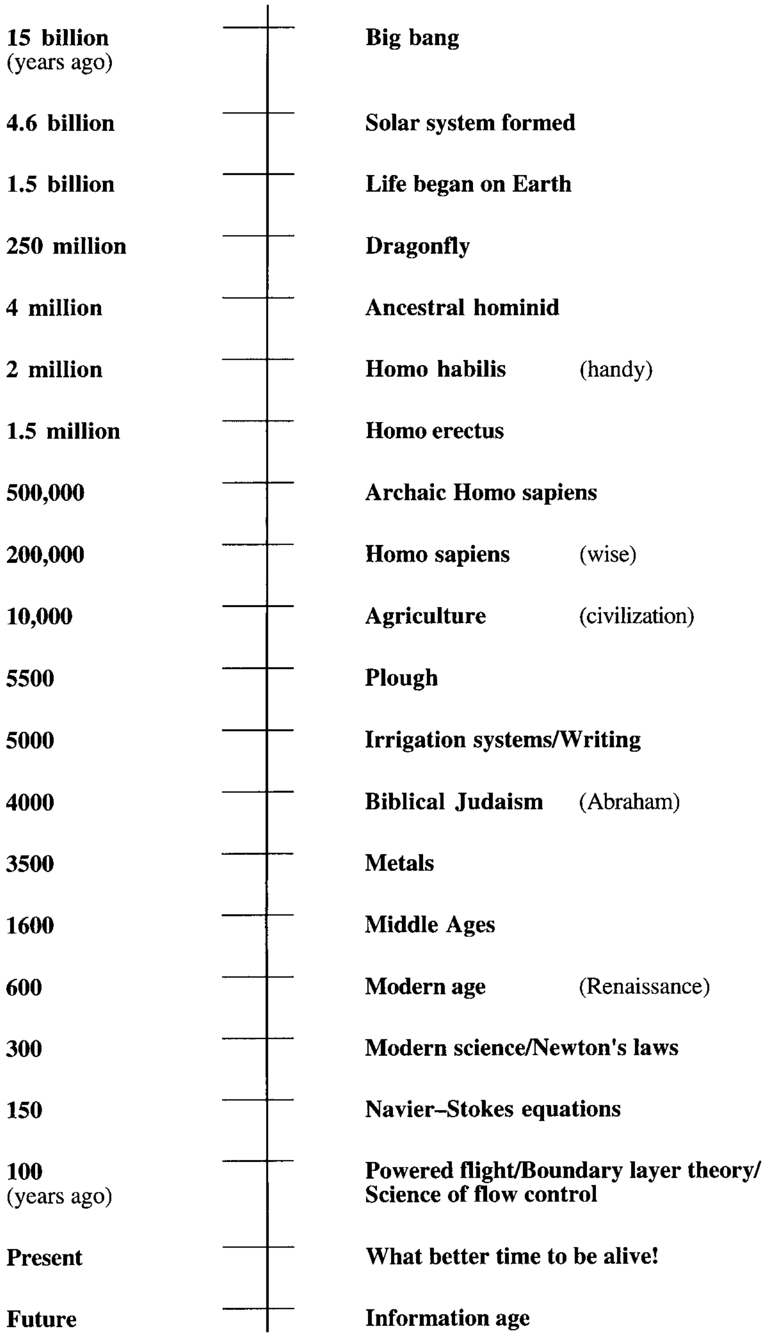


Figure 1.1: History of the universe timeline. All dates are approximate, and the timescale is highly nonlinear.

or Maxwell's theory of electromagnetics, the majority of physicists believed that the work of their successors *would be merely to make measurements to the next decimal place*. That was just before the theory of relativity and quantum mechanics were discovered!

Technology has its share of amusing anecdotes as well. In the 1860s, Abraham Lincoln's commissioner of patents recommended that the commission be closed in a few years because the rate of discovery had become so great that everything that needed to be discovered would have been discovered by then. The patent commission would simply have no future business. "Opportunity is dead! All possible inventions have been invented. All great discoveries have been made." In 1899—before the airplane, laser, and computer were invented—the commissioner of the U.S. Office of Patents, Charles H. Duell, urged President McKinley to abolish this office because "everything that can be invented has been invented." Foolish, fallacious statements like those are frequently attributed to various myopic patent officials of the past and are perpetuated even by the most respected writers and speakers of our time. We cite here three of the most recent perpetuators who all of course wanted only to show how ignorant and unimaginative the hapless patent officer must have been: Daniel E. Koshland, Jr., the editor-in-chief of the periodical *Science*, in an editorial on the future of its subject matter (Koshland 1995); the cyberseer and megaentrepreneur Bill Gates in the hardcover—but not the paperback—edition of the instant best-seller *The Road Ahead* (Gates, Myhrvold, and Rinearson 1995); and the president of the National Academy of Sciences, Bruce Alberts, in a fund-raising letter dated April 1997, widely distributed to 'friends of science' in the United States. The definitive history of the preceding and related apocryphal anecdotes was documented by Eber Jeffery, who in 1940 conducted an exhaustive investigation of their authenticity and origin. Jeffery traced the then widely circulated tales to a testimony delivered before the United States Congress by Henry L. Ellsworth, the commissioner of patents in 1843, who told the lawmakers that the rapid pace of innovation "taxes our credulity and seems to presage the arrival of that period when human improvement must end." According to Jeffery (1940), this statement was a mere rhetorical flourish intended to emphasize the remarkable strides forward in inventions then current and to be expected. Indeed, Commissioner Ellsworth asked the Congress to provide him with extra funds to cope with the flood of inventions he anticipated. Jeffery concluded that no document could be found to establish the identity of the mysterious commissioner, examiner, or clerk who thought that all invention was a thing of the past. This was not true then and is certainly not true now, for both science and technology have indeed an 'endless frontier' (Bush 1945; Petroski 1997).

Our own subfield of flow control provides a good rebuttal to the fluid mechanics critics. How much resources are spent annually to overcome the drag of air, water, and land vehicles and the fluid resistance in pipelines, ducts, and countless other man-made systems? How many airplane crashes could have been averted if lifting surfaces more resistant to stall had been designed? Can fighter aircraft achieve supermaneuverability? How much pollution is generated as a result of incomplete, inefficient combustion in furnaces, incinerators, internal combustion engines, gas turbines, and numerous other reactors? As mandated by the 1997 Kyoto Protocol, by the year 2012 the industrialized countries must reduce their emissions of greenhouse gases 6–8% *below* those produced in 1990. How can they achieve this target? How much does it cost to fly across continents at hypersonic or even supersonic speeds? Can we economically utilize ultrafast submarines, instead of snail-paced ships, for hauling people and commerce across the seas? For transport through urban areas whose already congested roads have no more room for growth, can we envision a personal helicopter (skycar) that, aided by a sophisticated network of computers, is as easy to navigate and safer to drive than the automobile? And how about medical applications such as artificial organs, microdosage delivery systems, and diagnostic tools? All these challenges are areas that future advances in flow control in particular and fluid mechanics in general, unforeseen to us today, could help overcome. The book edited by Lumley, et al. (1996) provides an excellent outline of the near-future prospects of 27 different fluid dynamics research areas, whereas the one edited by Gad-el-Hak, Pollard, and Bonnet (1998) focuses exclusively on flow control.

True, fluid mechanics will be a very different discipline during the third millennium. The entire field, together with much of the rest of the physical sciences, may be set for dramatic changes. In no small part, rapidly advancing computer technology will be responsible for those changes. As argued in the editorial by Gad-el-Hak and Sen (1996) and the paper by Gad-el-Hak (1998a), gigantic computers combined with appropriate software may be available during the twenty-first century to routinely integrate the full, instantaneous Navier–Stokes equations. The black box would prompt its operator for the geometry and flow conditions and would then present a first-principles numerical solution to the specific engineering problem, high-Reynolds-number turbulent flows included.

In a turbulent flow, the ratio of the large eddies (at which the energy maintaining the flow is input) to the Kolmogorov microscale (the flow smallest length scale) is proportional to $Re^{3/4}$ (Tennekes and Lumley 1972). Each excited eddy requires at least one grid point to describe it. Therefore, to adequately resolve, via direct numerical simulations (DNS), a three-dimensional flow, the required number of modes would be proportional to $(Re^{3/4})^3$. To describe the motion of small eddies as they are swept around by large ones, the time step must not be larger than the ratio of the Kolmogorov length scale to the characteristic rms velocity. The large eddies, on the other hand, evolve on a time scale proportional to their size divided by their rms velocity. Thus, the number of time steps required is again proportional to $Re^{3/4}$. Finally, the computational work requirement is the number of modes $\times$ the number of time steps, which scales with $Re^3$, that is, an order of magnitude increase in computer power is needed as the Reynolds number is doubled (Karniadakis and Orszag 1993). Because the computational resource required varies as the cube of the Reynolds number, it may not be possible to simulate very high-Reynolds-number turbulent flows any time soon (Karniadakis 1999).

Despite the bleak assessment above, one wonders whether gigantic computers combined with appropriate software will be available during the twenty-first century to routinely solve, using DNS, practical turbulent flow problems? The black box would prompt its operator for the geometry and flow conditions and would then generate a numerical solution to the specific engineering problem. Nobody, except the software developers, needs to know the details of what is going on inside the black box, not even which equations are being solved. This situation is not unlike using a present-day word processor or hand calculator. A generation of users of the Navier–Stokes computers would quickly lose the aptitude, and the desire, to perform simple analysis based on physical considerations, much the same as the inability of some of today's users of hand calculators to manually carry out long divisions. The need for rational approximations, so prevalent today in fluid mechanics teaching and practice, would gradually wither.

During the late 1990s, the supercomputer power approached the teraflop (i.e., $10^{12}$ floating-point operations per second). This is about right to compute a flow with a characteristic Reynolds number of $10^8$, sufficient to simulate the flow around an airfoil via DNS, around a wing via large-eddy simulation, or around an entire commercial aircraft via Reynolds-averaged calculation. It is anticipated that the 10-teraflop computer will be available by mid-2000, and the 100-teraflop machine by 2004, bettering the Moore's law by tripling—instead of doubling—the chip speed every 18 months. An exaflop ($10^{18}$ flops) computer is needed to carry out direct numerical simulation of the complete airplane (Karniadakis and Orszag 1993), and thus we are still a long way from that.

Silicon-based computer powers have manifested spectacular recent advances—something like a factor of 10,000 improvement in speed and capacity during the past 20 years.[2] If one is to extrapolate those recent advances to the next 50 years or so, using direct numerical simulations to solve the turbulence problem for realistic geometries and field Reynolds numbers may begin to approach feasibility. Unfortunately, however, silicon microchips are rapidly approaching their physical limits with little room for further growth. The smallest feature in a microchip is defined by its smallest linewidth, which in turn is related to the wavelength of light employed in the basic lithographic process that is used to create the chip. The linewidths of chips manufactured in 1999 is 180 nm, and most experts doubt that chips using current complementary metal oxide semiconductor (CMOS) technology can shrink below 50-nm linewidths—a size that could be reached around 2012 (Lerner 1999). There is even a natural—in contrast to a technological—barrier to extreme miniaturization (Schulz 1999). A recent report by a team of researchers from Lucent Technologies (Muller et al. 1999) has uncovered a troubling natural brick wall. The thin layer of silicon dioxide insulation that separates the various conducting or semiconducting components on a chip is rendered useless if its thickness falls below 0.7 nm or the equivalent of four silicon atoms across. At the current rate of progress, such a fundamental limit on the thinnest usable silicon dioxide gate dielectric will also be reached around 2012.

Fortunately, this kind of linear thinking may be misleading. Revolutionary computing machines that bear little resemblance to today's chip-based computers may be developed in the future. A recent article in *Science* (Glanz 1995) discusses five such futuristic computing concepts: quantum dots, quantum computers, holographic association, optical computers, and deoxyribonucleic acid (DNA) computers. Very recently, the prospect for molecular computing was unveiled (Collier et al. 1999; Service 1999; Markoff 1999). We elaborate below on the latter two computers as examples.

The DNA computer is a novel concept introduced and actually demonstrated only late in 1994 by Adleman, who in turn was inspired by Feynman's (1961) original vision of building even smaller submicroscopic computers. The idea for the massively parallel DNA computing system is to use the four basic chemical units of DNA (adenine, thymine, guanine, and cytosine, designated A, T, G, and C, respectively) as computing symbols and to utilize the genetic material for information storage and computations. Computer theorists argue that a problem could be set up by synthesizing DNA molecules with a particular sequence that represents numerical

[2] Although loosely related, this is consistent with the law named after the cofounder of Intel Corporation, Gordon Moore, who in 1965 predicted that the transistor density on a semiconductor chip would double and its price would halve roughly every 18 months. Incidentally, Moore's law has been bettered in 1997.

information and by letting the molecules react in a test tube, producing new molecules whose sequence is the answer to the problem. Thus, the same genetic machinery that generates living organisms could be used to solve previously unapproachable mathematical puzzles. Crude estimates indicate that a mere 500 g of DNA molecules (a human body contains about 300 g of deoxyribonucleic acid) suspended in 1000 l of fluid would have a memory equivalent to all the electronic computers ever made! In such primordial reacting soup, 4 months of manipulating the DNA molecules would yield an answer to a problem that would have required more operations than all those ever performed on all the conventional computers ever built—at least up to the mid-1990s.

Just as this book was going to the press, a research team from Hewlett–Packard company and the University of California at Los Angeles (Collier et al. 1999) announced that they have fashioned simple computing components no thicker than a single rotaxane[3] molecule, thus plunging deeply into a Lilliputian world that promises computers $10^{11}$ times as fast as today's most powerful personal computers. This infant field of research is termed *moletronics* or molecular electronics and uses chemical processes rather than light to form molecular-thin on–off switches. Future developments in moletronics will open new windows onto a once speculative but now increasingly probable vista of molecular-scale computers, sensors, and actuators.

To close this section on a positive note, neither fluid mechanics nor flow control appears to be approaching a pinnacle. The best is yet to come. Future computers will allow solutions to the most daunting problems in both fields, and rational designs based on first principles will be routine for the most complex fluid systems. Sophisticated reactive control systems consisting of a colossal number of microsensors and microactuators communicating with each other via massively parallel computers will in the future improve, by leaps and bounds, the fluids engineer's ability to reduce drag, increase lift, suppress flow-induced noise, enhance mixing, and achieve any other desired flow-control goal.

[3] Rotaxane is a synthetic organic compound created by chemists at the University of California at Los Angeles.

CHAPTER TWO

# Governing Equations

*No knowledge can be certain if it is not based upon mathematics.*
*(Leonardo da Vinci, 1452–1519)*

*You are not educated until you know the Second Law of Thermodynamics.*
*(Charles Percy (Baron) Snow, 1905–1980)*

## PROLOGUE

There is no doubt that rational design (i.e., based on first principles) of flow-control devices is always preferable to a trial and error approach. Rational design of course is not always possible owing to the extreme complexity of the equations involved, but one tries either analytically or, more commonly to date, numerically. The search for useful compliant coatings, discussed in Chapter 7, is a case in point. The window of opportunity for a successful coating is so narrow that the probability of finding the right one by experimenting is near nil. Fortunately, the analytical and numerical tools to guide the initial choice for a transition-delaying compliant surface are currently available. On the other hand, the flowfield associated with a typical, deceivingly simple vortex generator for airplane wings is so complex that its design is still done to date more or less empirically.

The proper first principles for flow control are those for fluid mechanics itself. The principles of conservation of mass, momentum, and energy govern all fluid motions. Additionally, all processes are constrained by the second law of thermodynamics. In general, a set of partial, nonlinear differential equations expresses those principles, and, together with appropriate boundary and initial conditions, constitute a well-posed problem. In the following we provide a simple derivation of the general form of the three conservation relations. Readers desirous of more details could consult any advanced textbook in fluid dynamics (e.g., Batchelor 1967; Hinze 1975; Landau and Lifshitz 1987; Tritton 1988; Sherman 1990; Kundu 1990; Currie 1993; Panton 1996).

## 2.1 The Fundamental Equations

Each of the fundamental laws of fluid mechanics, conservation of mass, momentum, and energy, will be expressed first as an integral relation and then as a differential