Chapter 1

Introduction

Fluid flow is important in many fields of engineering, industries and scientific research such as meteorology, astronomy, chemistry, geology and physics. As a result, the interest in fluid mechanics by scientists and engineers has continued to grow throughout many years of study. Recently, the emphasis of interest has changed from that in traditional fluid mechanics. This change is taking place mainly due to two reasons. Firstly, with the development of fast and large-capacity computing technology, numerical methods have become a powerful tool for fluid mechanists. In fact, it has developed to a new field of flow study, the computational fluid dynamics (CFD). Secondly, the microscopic fluid flow study (microfluidics) is rapidly expanding, motivated by the demand from biomedical study and chemical analysis, and made possible by the micromachining technology developed over the past decade [1,2,3,4]. Finally, the active control of fluid flows has recently become a hot topic in fluid mechanics [5,6,7,8], as opposed to the passive control in the past [9,10,11]. This is because of the emerging CFD and also the fast development of available hardware, due to the availability of the microfabrication technology.

1. 1 Fluid Mechanics Measurements

Some form of flow measurements are always required to improve our understanding of the physical processes in turbulent and three-dimensional flow systems, as well as to determine the flow quantities needed in a variety of industrial applications. Even the advent of sophisticated numerical methods in CFD for studying and predicting turbulent flow has not diminished the requirement for flow measurement, but rather enhanced this need because the development of turbulence models still requires much experimental input and eventually verification in many different flows.

Many different flow parameters are required to describe fluid flows. The most important ones are pressure, p, and flow velocity, U. From these two parameters, many other physical parameters can be computed for a single-phase flow. For example, the lift force is a function of pressure; the surface shear stress is proportional to the normal gradient of the flow velocity on the surface; the volumetric flow rate is the integral of the flow velocity over a cross-sectional area. This is probably why pressure sensors and flow velocimeters (hot-wire and hot-film anemometers, Laser-Doppler Velocimeter) are the most widely used instruments in fluid mechanics measurement.

In reality, however, measurement of the spatial and temporal distribution of pressure and velocity is complicated and sometimes, not possible. Meanwhile, this type of measurement and correlation is not always necessary in order to know a specific physical parameter. For example, it is possible to perform shear stress and volume flow rate measurements without knowing the flow velocity field. This is why there exist many other instruments besides pressure sensors and flow velocimeters such as shear stress sensors and flow meters.

1.2 Flow Control

1.2.1 Basic Fluid Mechanics Concept

Some basic fluid mechanics notations that are used in this section and throughout the thesis are briefly explained here.

Laminar and Turbulent Flow In laminar flow, fluid particles move very smoothly parallel to each other. There is basically no mixing between different layers of fluids. Therefore, a dye stream injected in a laminar flow field would move in a thin line. Low velocity flow in a smooth channel is usually laminar.

Turbulent flow is an irregular condition of flow in which fluid particles move randomly and the various quantities show a random variation with time and space coordinates, so that statistically distinct average values can be discerned [12]. Usually turbulent flow occurs at high velocity. Much effort has been spent in the study of this difficult topic in fluid mechanics. For example, computational fluid dynamics has been introduced to study and predict turbulence. In addition, experimental methods are also used to investigate the turbulence structures and explore the possibility of turbulence manipulation.

Boundary Layer and Shear Stress Boundary layer is defined as the thin layer of viscous fluid adjacent to the solid surface which has a velocity shear. The velocity u is zero at the surface and increases with increasing distance (y) from the surface. The boundary layer thickness δ is defined as the normal distance from the surface to a point where the local fluid velocity is 99% of the free stream velocity. Boundary layers are thinner at the leading edge of a flat plate or the entrance of a pipe and thicker toward the trailing edge. Flow in boundary layers is generally laminar at the leading or upstream portion and turbulent in the trailing or downstream portion. Inside the turbulent boundary layer, there is an extremely thin layer of fluid attached to the surface called the viscous sub-layer in which the velocity distribution in direction normal to the surface is linear.

The shear stress in laminar flow is defined as

$$\tau = \mu \left.\frac{\partial u}{\partial y}\right|_{y=0} \tag{1.1}$$

and the shear stress in turbulent flow is defined as

$$\tau = (\mu + \rho\varepsilon) \left.\frac{\partial u}{\partial y}\right|_{y=0} \tag{1.2}$$

where ε is the eddy viscosity. The shear stress in turbulent is higher than that in laminar flow not only because of the eddy viscosity, but also because of the high velocity gradient in the viscous sub-layer.

Reynolds Number In discovering the difference between laminar and turbulent flows in 1883, Osborne Reynolds noted that the quality of the flow in a pipe of diameter D depended on the dimensionless parameter UD/ν, where U is the average fluid velocity, $\nu \equiv \mu/\rho$ is the kinematic viscosity, μ is the dynamic viscosity, and ρ is the density of the fluid. More generally, the Reynolds number is defined as

$$\mathbf{Re} = \frac{Ul}{\nu} \tag{1.3}$$

where l is the characteristic length scale. In a pipe flow, the flow is usually turbulent for **Re** > 2000. In flow over a flat plate, when the plate length is taken as the characteristic length, the transition from laminar to turbulent commonly occurs at $3\times10^5 < \mathbf{Re} < 6\times10^5$. Two flows are considered to be similar if their Reynolds numbers are identical in a geometrically similar, incompressible (ρ = constant) pipe flow.

Flow Separation For a flat plate submerged in a flow, the boundary layer remains attached to the surface and grows throughout its length. However, this is not always the case when the fluid path is oblique to the surface [13]. For example, for the blunt-nosed body of Figure 1.1(a) the boundary layer detaches, separating from the surface at the up-stream end and produce a wake, while for the round-nosed body of Figure 1.1(b), the boundary layer remains attached to the surface. The airfoil of Figure 1.1(c) experiences accelerating flow from point A to B and deceleration from point B to the trailing edge. At point C, known as the separation point, the velocity gradient is zero, i.e.,

$$\left.\frac{\partial u}{\partial y}\right|_{y=0} = 0 \tag{1.4}$$

and the flow actually reverses in direction between point C and D. The corresponding pressure gradients shown in the figure come from the Bernoulli's equation in potential flow theory. Separation can only occur in decelerating flow. Beyond the separation point the pressure gradient is said to be adverse. From Eq. (1.1), one would conclude that the shear stress at a separation point is zero. However, this is true only in two-dimensional flow. For three-dimensional flow, the shear stress usually has a local minimum at the separation point, because there may still be a gradient of the velocity component in the second dimension.

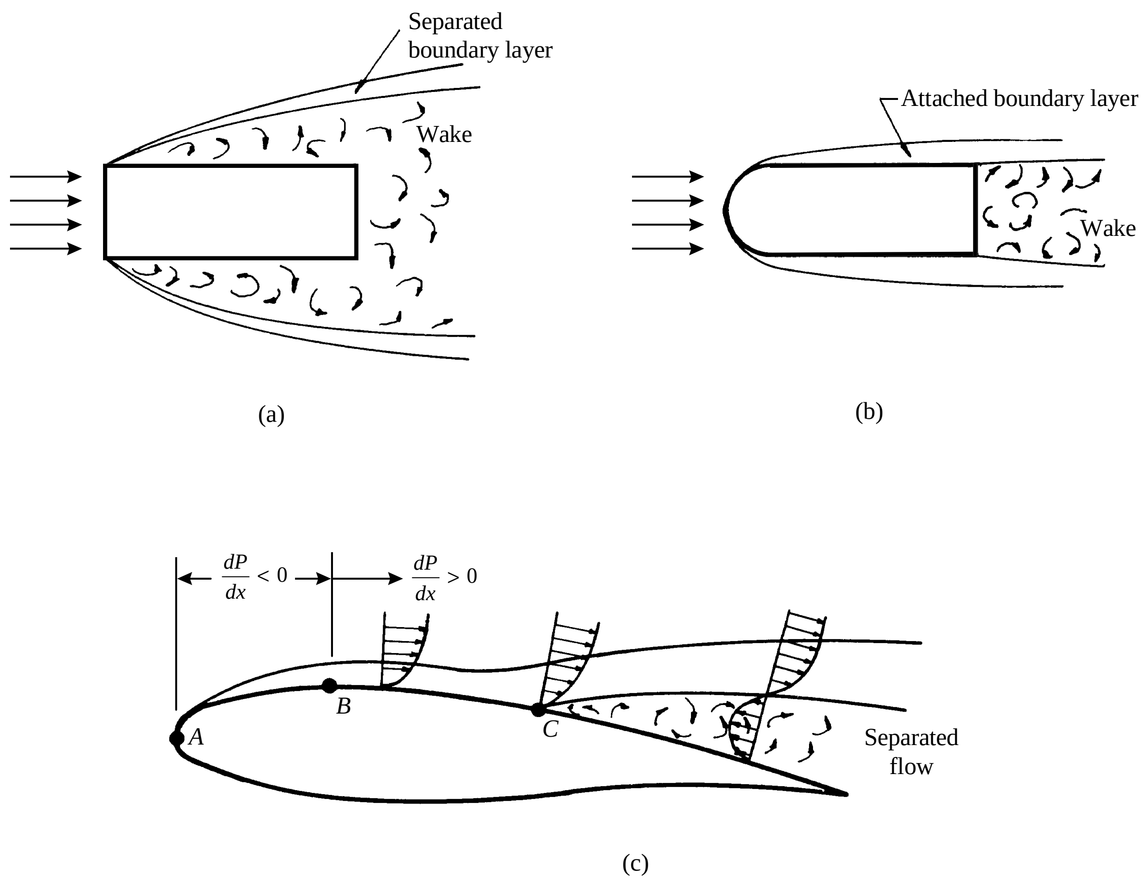

Figure 1.1 Flow over (a) blunt-nosed body, (b) round-nosed body and (c) airfoil.

1.2.2 Flow Control

Flow control is currently attracting increased attention in connection with a variety of applications. In flow control application one may want to destabilize the flow, in order to achieve better mixing, or to stabilize the flow in order to eliminate undesirable unsteady loads. Several studies have appeared on the subject, and one can classify the techniques used into two major categories: passive control, in which flow control is achieved by altering the geometry of the flow; and active control, in which a time-dependent forcing is applied to the flow, by means, for instance, of a loudspeaker.

Passive control can suppress unsteadiness in a flow [14,15,16]. In practical application, however, no matter how careful the design is, flow separation and unsteadiness behind moving bodies are often unavoidable because of maneuvering motion, or encountering ambient turbulence.

Active control can be divided into open-loop schemes, in which the forcing is a prescribed function of time, and closed-loop schemes, in which the forcing is a function of some real-time measurement of the response of the flow. Open-loop schemes rely on an accurate knowledge of the basic fluid mechanics of the problem in order to prescribe the appropriate forcing function for the controller [17]. In closed-loop schemes, on the other hand, a sensor is placed in the flow field, and its output, after going through a controller, is fed back into the actuator [18]. Closed-loop schemes thus do not necessarily require the detailed knowledge of fluid mechanics that open-loop schemes do. However, in addition to the issue of closed-loop stability, the very important question of observability of the flow remains open. In fact, Roussopoulos [19] recently presented convincing evidence that, when a single sensor is used, the flow is not observable, in the sense that unsteady patterns are present without being detected by the sensor. Therefore, in order to perform closed-loop active control, it is essential to have a large number of sensors for the detection of flow patterns.

1.3 MEMS and Its Application in Fluid Mechanics

The emerging micro-electro-mechanical system (MEMS) technology has been used to fabricate mechanical structures in micrometer scales, such as beams, diaphragms, grooves, orifices, sealed cavities, pyramids, needles, springs, gears, joints and motors. It provides us with micro-sensors and micro-actuators which match the length scales of the investigated phenomena in the exploration of all areas of science so that enough spatial resolution can be achieved for sensing and effective momentum and energy transfer to the controlled subjects can be accomplished for actuation. Furthermore, these miniature transducers can be integrated with microelectronics to complete the loop of sensing, information processing, actuation and sensing on a single chip. This type of mass-producible systems enables us to perform real-time control of time-varying events common in fluid dynamics.

The basic MEMS fabrication techniques includes bulk and surface micromachining, wafer bonding and micromolding (LIGA). Detailed information about MEMS fabrication techniques can be found in many excellent reviews papers [20,21]. Here, silicon bulk and surface micromachining technologies are briefly introduced because they will be used throughout the thesis. Moreover, the materials commonly used in these technologies and the compatibility issue of the MEMS processes with microelectronics will be discussed. Finally the potential MEMS applications in fluid mechanics are listed.

1.3.1 Silicon Micromachining

Si micromachining technology is dominant in the fabrication of MEMS devices because of its similarity with the Si microelectronics fabrication technology. As a matter of fact, it is regarded as being derived from IC technology. Historically, Si micromachining is divided into two categories, bulk and surface micromachining.

Bulk Micromachining Silicon bulk micromachining uses wet and dry silicon etching techniques, with etch masks and etch stops, to sculpt mechanical devices from a silicon wafer. The mixture of hydrofluoric acid, nitric acid and acetic acid (HNA) is an isotropic silicon etchant with silicon nitride as the etch mask. Certain other chemicals, such as ethylene-diamine-pyrocatechol with water (EDP or EPW), tetramethyl ammonium hydroxide (TMAH), hydrazine solution and potassium hydroxide (KOH) solution, etches in (100) and (110) silicon crystallographic directions much faster than in the (111) direction, which allows the design of microstructures to be naturally bounded by {111} crystalline planes. Silicon dioxide and silicon nitride generally have very low etch rate in these anisotropic etchants and make good etch masks. The vertical etch stop can be heavily boron-doped layer buried under epitaxial layer, silicon dioxide in SIMOX wafers and p-n junction (for electrochemical etching). It is generally agreed that Si bulk micromachining using wet chemical etching is a mature technology and many Si microstructures including beams, diaphragms, nozzles, etc. have been made. These microstructures have formed the building blocks of many MEMS devices.

Nevertheless, there are some disadvantages for bulk micromachining using wet anisotropic etching. For example, the geometry that can be made by are generally limited by the silicon crystalline orientations; bulky corner compensation structures are often needed in order to make convex structures such as beams; the choices of etch masks are extremely limited. In contrast, dry etching processes do not have these problems and have recently attracted more attention. These include laser drilling, reactive ion etching (RIE), ion milling and even micro electro-discharge-machining (EDM).

Surface Micromachining In silicon surface micromachining, microstructures are fabricated on the surface of the Si substrate by consecutive deposition and patterning of thin-film structural and sacrificial layers. The Si substrate, however, only serves as a mechanical support and usually does not participate in the processing. At a certain stage, the sacrificial layers are removed by wet or dry etching that does not attack the structural layers. Silicon dioxide is the most often used sacrificial materials, while polysilicon and some metals are occasionally used as sacrificial materials. The most common structural materials are polysilicon and silicon nitride.

1.3.2 Integration with IC

The integration of MEMS devices with IC has many advantages. First, it can greatly reduce the total number of external electrical leads. This is especially important for a distributed control system where a large number of sensor arrays are involved. Second, on chip electronics reduces the electromagnetic interference from outside and parasitic effects from the external leads. Finally, since integration is a batch fabrication process, it saves time and reduces the production cost.

The integration of MEMS devices with IC is also very challenging because they usually do not share the same fabrication process. It requires careful design of the whole fabrication process to ensure good compatibility. Major considerations should be on the sequence of the processing steps, effect of high temperature post-processing on the electronics, protection of fabricated devices during the fabrication of other types of devices and the effect of surface profile of fabricated devices on the fabrication of other types of devices.

1.3.3 MEMS in Fluid Mechanics

Many MEMS devices have been developed in the past decade for fluid flow study, including pressure sensors and various types of flow sensors. Among them, Si piezoresistive pressure sensors have been successfully used in fluid mechanics measurements. Other devices, such as MEMS anemometers developed by other researchers, do not have comparable performances as their conventional counterparts. This does not mean that MEMS technology is not suitable for fluid mechanics. It only implies that more effort needs to be put in their development. In fact, MEMS technology can be used to solve the most difficult problems in fluid mechanics such as flow control [22,23,24,25]. The reason is twofold. First, the flow structures are generally small. As we pointed out earlier, length scale matching between the transducers used and the investigated phenomena is essential. Therefore, the transducers used in flow control have to be small. Second, the capability of providing large numbers of sensors and actuators by MEMS technology allows us to perform active distributed control, which is the only effective way of flow control due to the distributive nature of the flow. This potential, however, remains to be explored.

1.4 Overview of Chapters

Chapter 2 describes the design and fabrication of micromachined polysilicon hot-wire anemometers. These hot wires have the same basic structure as that of a conventional hot wire, but with greatly reduced dimensions. They are different from many existing surface mount micromachined hot-wires which can only be used to measure the velocity a few microns above the surface. Many performances including the sensitivity and frequency response are improved. More importantly, they are batch-fabricated and mass-producible, as compared to the painstaking manual fabrication of conventional hot wires. A thorough calibration has been presented to validate the use in flow velocity measurement.

Chapter 3 presents the design and fabrication of the vacuum-isolated flush-mounted hot-film shear-stress sensor. Detailed heat transfer analysis for this special structure combined with calibration results has clarified the applicable dynamic range of the sensor. The theoretical model also points out possible improvement on the performances of this type of sensors.

As a demonstration of the application of the micromachined shear stress sensors, we have fabricated an array of such sensors to map out the wall shear stress distribution in a fully-developed 2-D channel flow. The use of the shear stress sensor array for underwater measurement has also been explored. These are all presented in Chapter 4.

Chapter 5 is dedicated to the integration of the shear stress sensors, micromachined micro-actuators and the CMOS control electronics for turbulent flow drag-reduction study. Emphasis is on the compatibility of the processing steps for the shear stress sensor with those for the other two types of devices.

Chapter 6 describes our effort on the development of a new microfabrication technology that enables the integration of MEMS devices, including CMOS electronics, on a flexible polyimide skin. The major lead failure that occurred in previously-reported technologies has been eliminated through the proper shaping of Si islands. Moreover, Si islands as small as 100 μm can be defined with good accuracy, which allows the skins to be applied on small surfaces with large curvatures. The first application of this technology in aerodynamics has produced a flexible shear stress sensor array that was used for the real-time measurement of the shear stress distribution on 3-D surfaces.

Bibliography

[1] S. C. Terry, J. H. Jerman, and J. B. Angell, "A Gas Chromatographic Air Analyzer Fabricated on a Si Wafer," *IEEE Trans. Electron. Devices*, Vol. ED-26, pp. 1880-1886, 1979.

[2] J. Liu, Y. C. Tai, K. C. Pong, and C. H. Ho, "Micromachined Channel/Pressure Sensor Systems for Microflow Study," *Tech. Digest 7th Int. Confer. Solid-State Sensors & Actuators (Transducer' 93)*, Yokohama, Japan, pp. 995-997, 1993.

[3] P. Gravesen, J. Branebjerg, and O. S. Jensen, "Microfluidics - a Review," *Proc. MME' 93*, 1993.

[4] E. B. Arkilic, M. A. Schmidt, and K. S. Breuer, "Gaseous Flow in Microchannels," *ASME Application of Microfabrication to Fluid Mechanics, 1994 Int. Mech. Eng. Congress and Expo.*, Chicago, pp. 57-66, 1994.

[5] P. Moin, J. Kim, and H. Choi, "On the Active Control of Wall-Bounded Turbulent Flows," AIAA Paper 89-0960, 1989.

[6] P. R. Bandyopadhyay, "Development of a Microfabricated Surface for Turbulence Diagnostics and Control," *ASME Application of Microfabrication to Fluid Mechanics, 1994 Int. Mech. Eng. Congress and Expo.*, Chicago, pp. 67-74, 1994.

[7] B. F. Farrell, P. J. Ioannou, "Turbulence Suppression by Active Control," *Phys. Fluids*, Vol. 8 (5), pp. 1257-1268, 1996.

[8] H. A. Carlson and J. L. Lumley, "Active Control in the Turbulent Wall Layer of a Minimal Flow Unit," *J. Fluid Mech.*, Vol. 329, pp. 341-371, 1996.

[9] S. R. Park and J. M. Wallace, "Flow Alteration and Drag Reduction by Riblets in a Turbulent Boundary-Layer," *AIAA J.*, Vol. 32 (1), pp. 31-38, 1994.

[10] P. Vukoslavcevic, J. M. Wallace, and J. L. Balint, "Viscous Drag Reduction Using Streamwise-Aligned Riblets," *AIAA J.*, Vol. 30 (4), pp. 1119-1122, 1992.

[11] B. Lazos and S. P. Wilkinson, "Turbulent Viscous Drag Reduction with Thin-Element Riblets," *AIAA J.*, Vol. 26 (4), pp. 496-498, 1988.

[12] J. Hinze, *Turbulence*, 2nd ed., MacGraw-Hill, 1975.

[13] D. R. Pitts and L. E. Sissom, *Heat Transfer*, McGraw-Hill, 1977.

[14] Y. Y. Chen and J. T. Templin, “Suppression of Spatial Waves by Distortion of Jet Velocity Profile,” *Phys. Fluids*, Vol. 17, pp. 2124-2125, 1974.

[15] M. M. Zdravkovich, “Review and Classification of Various Aerodynamic and Hydrodynamic Means of Suppressing Vortex Shedding,” *J. Wind Eng. Indust. Aero.*, Vol. 7, pp. 145-189, 1981.

[16] P. J. Strykowski and K. R. Sreenivasan, “On the Formation and Suppression of Vortex Shedding at Low Reynolds Number,” *J. Fluid Mech.*, Vol. 218, pp. 71-107, 1990.

[17] P. T. Tokumaru and P. E. Dimotakis, “Rotary Oscillation Control of a Cylinder Wake,” *J. Fluid Mech.*, Vol. 224, pp. 77-90, 1991.

[18] J. E. Ffowcs Williams and B. C. Zhao, “The Active Control of Vortex Shedding,” *J. Fluid Struct.*, Vol. 3, pp. 115-122, 1989.

[19] K. Roussopoulos, “Feedback Control of Vortex Shedding at Low Reynolds Number,” *J. Fluid Mech.*, Vol. 248, pp. 267-296, 1993.

[20] K. E. Petersen, “Silicon as a Mechanical Material,” *Proc. IEEE*, Vol. 70 (5), pp. 420-456, 1982.

[21] L. O’Connor, “MEMS: Microelectromechanical Systems,” *Mechanical Engineering*, Vol. 114, pp. 40-47, 1992.

[22] S. A. Jacobson and W. C. Reynolds, “Active Boundary Layer Control Using Mounted Surface Actuators,” *Bulletin of American Physical Society*, Vol. 38, pp. 2197-, 1993.

[23] B. L. Smith and A. Glezer, “Jet Vectoring by Synthetic Jet Actuators,” *Bulletin of American Physical Society*, Vol. 40, pp. 2025-, 1995.

[24] J. M. McMichael, “Progress and Prospects for Active Flow Control Using Microfabricated Electro-Mechanical Systems (MEMS),” AIAA Paper 96-0306, 1996.

[25] C. H. Ho and Y. C. Tai, “REVIEW: MEMS and Its Application for Flow Control,” *J. Fluid Eng.*, Vol. 118, pp. 437-447, 1996.