Challenging Issues in Separated and Complex Turbulent Flows

by

M. Kiya, O. Mochizuki and H. Ishikawa

Division of Mechanical Science

Graduate School of Engineering, Hokkaido University

Sapporo, 060-8628; Japan

ABSTRACT

Challenging issues on separated flows at high Reynolds numbers are discussed for several prototype flows: separated-and-reattaching flows; separated flows around cylindrical bluff bodies; separated flows around axisymmetric and plane-symmetric bluff bodies. These flows are characterized by large-scale vortices which interact with each other or with a solid surface. Structure and dynamics of the large-scale vortices are discussed, together with the low-frequency modulation of the vortices whose time scale is an order of magnitude greater than the vortex-shedding period. It is argued that the modulation is an intrinsic property of the separated flows. The advent of computers and laser-applied technology have been making it more and more efficient and economical to obtain spatio-temporal structure of vortices in the separated flow. What is lacking is a physical model which predict essential properties of the separated flows such as the base pressure. This is because the base pressure is determined by the overall dynamics of the near wake flows. A strategy of interactive control of unsteady separated flows which assumes the existence of a precursor of large-scale separation is also discussed.

1. INTRODUCTION

In this paper separated and complex turbulent flows are defined as flows with large-scale separation of boundary layer from a solid surface at high Reynolds numbers. These flows are characterized by the formation of large-scale rolling-up vortices and unsteadiness characterized by the motion of the vortices which interact with each other or with a solid surface. There are an enormous number of these flows which are encountered in engineering applications. The present paper does not intend to give an extensive review on these flows but to discuss some fundamental properties and physical models of a few prototypes of the separated flows, with the expectation that such information will serve to understand separated and complex turbulent flows in general.

Separated and complex turbulent flows, which will hereinafter be referred to as separated flows, have extensively been studied by experiments and numerical simulations to yield distributions of statistical flow properties such as time-mean velocities, pressure, Reynolds stresses, correlations, and spatio-temporal structure of large-scale vortices. These are *experimental* results, which are useful in the design of flow apparatus, but to have experimental results is not equivalent to understand the flow. The advance of numerical simulations and experiments aided by high technology such as Lasers and computers is just to make it rapid and economical to obtain the experimental results. A flow is understood when a physical or mathematical model which can predict essential properties of the flow is constructed. In this sense we have not yet understood separated flows. This is because unsteadiness due to the motion of large-scale vortices and their three-dimensionality are characteristic of separated flows.

Separated flows can be classified into two categories. One is the flow with reattachment, while the other is the flow without reattachment. Typical examples of the former is the flow over a backward-facing step and the leading-edge separation bubbles of aerofoils and blunt plates or blunt circular cylinders, while those of the latter are the flow around cylindrical bluff bodies such as circular cylinders and normal plates. The former is characterized by the interaction between vortices and the solid surface, while the latter is characterized by the interaction between vortices shed from the separation points.

In this paper the following flows are chosen as the prototype of separated turbulent flows: separated-and-reattaching flows; separated flows around cylindrical bluff bodies; three-dimensional separated flows around axisymmetric and non-axisymmetric bluff bodies. Low-frequency unsteadiness in these flows and active control of separated flows are also discussed. Mention will be made of important aspects which await laser-applied measurements, together with the need for a physical or mathematical model which can predict essential properties of the flow.

2. SEPARATED-AND-REATTACHING FLOWS

We consider the flow generated by boundary-layer separation from the square-cut leading edge of a blunt plate or a blunt circular cylinder of semi-infinite length, whose centerline is aligned with the main flow. In the time-mean sense the separated shear layer reattaches on the solid boundary to form a closed recirculating zone, thus being referred to as a separated-and-reattaching flow or separation bubble. This is the simplest configuration because the flow is dependent only on Reynolds number once the geometry of the body has been defined. It is not true in the separation bubble behind a backward-facing step which is dependent on properties of the approaching boundary layer and the expansion ratio of the flow passage. It may be noted that nominally two-dimensional and axisymmetric separation bubbles have basically similar properties.

Main features of the separation bubble of a blunt plate with the square-cut leading edge will be discussed. The boundary layer along the front face of the body is laminar up to sufficiently high Reynolds numbers because this is accelerated towards the corner of the leading edge. The boundary layer separates from the edge, being shed downstream as a separated shear layer. The shear layer rolls up by the Kelvin-Helmholtz instability to form rectilinear vortex tubes whose axis is aligned with the edge; these vortices are called spanwise vortices. The spanwise vortices merge to become larger and larger with increasing longitudinal distance from the edge. At the same time the spanwise vortices deform in the spanwise direction, being rapidly three-dimensionalized to develop turbulence. This process is basically the same as that of a plane mixing layer.

The difference between the separated shear layer and the plane mixing layer is that large-scale vortices in the former impinge on the surface of the body at a certain longitudinal distance from the edge, being shed downstream without experiencing further merging. This position of impingement is near the time-mean reattachment position of the shear layer, which is defined as the longitudinal position at which the time-mean streamline starting from the edge reattaches on the surface. The pressure fluctuation generated by the impingement of the vortices propagates upstream to be accepted at the sharp leading edge to generate vorticity fluctuation which enhances the rolling-up of the shear layer. The resulting large-scale vortices subsequently impinge on the surface. In this sense, the leading-edge separation bubble is a self-excited flow maintained by the feedback loop (Kiya et al. 1997). The feedback loop seems to be the case in nominally two-dimensional and axisymmetric separation bubbles. The feedback mechanism is a working hypothesis, having not been confirmed by experiments or numerical simulations. It is a challenge to obtain experimental evidence of the feedback loop by spatio-temporal measurements of the velocity, vorticity and pressure fields.

The number of merging of spanwise vortices up to the impingement position, the length scale of the impinging vortices, and the frequency of their shedding F_v are related to the height of the separated shear layer from the surface h (Sigurdson 1995). The height is, on the other hand, related to the surface pressure just downstream of the edge, which is called the base pressure p_b. Assuming that the pressure within the separation bubble is constant in the direction normal to the surface, the velocity at the edge of the shear layer U_s is given in the form $U_s = kU_\infty$, where U_∞ is the main-flow velocity, $k = (1 - C_{pb})^{1/2}$ and C_{pb} is the base-pressure coefficient. Sigurdson (1995) argues that the vortex-shedding frequency is determined from an empirical relation $F_v h/U_s$ = constant, which is the case for vortex-shedding frequency of cylindrical bodies. This formula can be employed in the separation bubble because we have a vortex street, although it is symmetric, if we takes into account corresponding image vortices within the body. On the other hand, the assumption of the feedback loop yields a relation $F_v x_R/U_c$ = constant, where x_R is the distance between the edge and the time-mean reattachment position (the reattachment length) and U_c is the average velocity of convection of rolling-up vortices in the shear layer (Kiya et al. 1997). With a reasonable assumption that h and U_s are proportional to x_R and U_c, respectively, the two equations are equivalent. We have no theoretical means to determine the base pressure p_b, height h and length x_R of the separation bubble.

The base pressure is related to the shape of the separated shear layer, especially its curvature, near the separation edge; the higher the curvature, the lower is the base pressure if the main-flow velocity is fixed. The shape of the shear layer is determined by the balance of out-flow by entrainment from the separation zone and the in-flow from the reattachment region, the inflow being the reverse flow along the surface. Thus the shape of the separated shear layer depends on the overall dynamics of flow in the recirculating region; the feedback loop is also included in this dynamics. The point is that we have not yet understood the overall dynamics to the extent that the parameters p_b, h and x_R van be predicted.

The frequency of vortex shedding F_v can probably be predicted by the inviscid linear stability analysis based on an assumed velocity profile in the separation bubble at sufficiently high Reynolds numbers (Huerre & Monkewitz 1990). The absolute instability is expected for the velocity profile with sufficiently high reverse-flow velocity. Moreover, the global instability analysis, which includes the effect of viscosity, for the steady separation bubble will predict a critical Reynolds number and the fundamental frequency at the onset of time-dependent flow. The critical Reynolds number for the separation bubble of a blunt plate (based on the thickness) is known to be approximately 320, based on the main-flow velocity and thickness of the plate (Sasaki & Kiya 1991). These instability analyses will enhance our understanding on the mechanism of the vortex shedding.

Sinusoidal forcing of separation bubbles yields further information on their flow physics. An example is the forcing of the leading-edge separation bubble of a blunt circular cylinder (Sigurdson 1995; Kiya et al. 1997). The forcing is made by a sinusoidal disturbance generated by an oscillating jet through a thin slot along the separation edge. The velocity fluctuation at the edge of the laminar boundary layer at the separation edge is $q = q_F \sin(2\pi F t)$, where q is the velocity component in a plane containing the axis of the cylinder, q_F and F are the amplitude and frequency of forcing, and t is time.

The reattachment length x_R plotted against the frequency F attains a minimum at a particular value $F = F_m$ = (1.6-2.1) U_∞/d for a fixed root-mean-square amplitude $q_F' = q_F/\sqrt{2}$. It should be noted here that there are two types of instability in the separation bubble. One is the Kelvin-Helmholtz instability and the other is the shedding-type or impinging-type instability (Sigurdson 1995; Nakamura & Nakashima 1986). The fundamental frequency of the initial KH instability F_{KH} scales to the momentum thickness of the shear layer at the separation edge and the velocity

U_s, thus being a function of Reynolds number. On the other hand, the fundamental frequency of the shedding-type instability is the vortex-shedding frequency F_v, being fairly constant at sufficiently high Reynolds numbers. The most-effective frequency F_m is much smaller than F_{KH} and greater than but closer to F_v.

Sigurdson (1995) argues that the shedding-type instability is the primary mode of instability in the separation bubble and thus the frequency F_m should be of the same order as that of the shedding-type instability. On the basis of the feedback loop and another assumption on the relation between the minimum reattachment length and the wavelength of the sinusoidal disturbance, Kiya et al. (1997) show that $F_m/F_v = 2^n$, where n is the number of merging of rolling-up vortices until the reattachment position, not being determined in the framework of this theory. The value of n appears to decrease as the amplitude q_F' increases. These heuristic models need be mathematically formulated to yield a relation between n and q_F'.

3. SEPARATED FLOW AROUND CYLINDRICAL BLUFF BODIES

Flow around cylindrical bluff bodies such as a circular cylinder at sufficiently high Reynolds numbers is characterized by the interaction between shear layers emanating from two primary separation points. From engineers' point of view, the time-mean and fluctuating drag and side forces, and the vortex-shedding frequency are among the most important properties. These properties have been obtained by experiments and numerical simulations. However, we have no theory which can predict the forces and frequency without any empirical input in a range of Reynolds number where the vortex shedding occurs in the near wake. A theory of drag of a circular cylinder is constructed from the first principle by Smith (1979) on the assumption of steady and symmetric laminar flow. The predicted the drag and base pressure are in excellent agreement with results of numerical simulations of steady symmetric flow (Sychev et al. 1998). However, the predicted drag is much lower than the drag obtained by experiments and numerical simulations which include the alternate vortex shedding. This means that the unsteadiness of flow in the near wake caused by the vortex shedding plays a crucial role in the theory of drag at high Reynolds numbers. We have not yet constructed such a theory.

There exist inviscid wake models which yield the time-mean pressure distribution along the wetted surface of a bluff body if the boundary-layer separation point and the pressure there, that is the base pressure, is given beforehand (Zdravkovich 1997). For bluff bodies with salient edges such as a normal flat plate, only the base pressure is needed. To calculate the separation point of the boundary layer we need to know the pressure distribution on the surface, which is possible if the shape of the separated shear layer is known. The shape of the shear layer, on the other hand, depends on the separation point and the base pressure. The most crucial parameter is the base pressure. If the base pressure is given, the separation point can be calculated by the boundary-layer theory by considering the effect of the outer flow. The base pressure depends on the overall dynamics of the near wake. The near-wake dynamics is not yet understood to the extent that the base pressure and the vortex-shedding frequency can simultaneously be predicted, although a great amount of information on spatio-temporal vortex structures have been obtained by experiments and numerical simulations. What is needed seems to find a new way how we should look at the near-wake vortex structure in view of construction of the theory of base pressure and drag.

The frequency of vortex shedding appears to be predicted by the inviscid linear stability theory for an assumed velocity profile with reverse flow. The fundamental frequency predicted by the theory is in good agreement with vortex-shedding frequency (Huerre & Monkewitz 1990; Asai et al. 1996). A global instability analysis with viscous effects included is expected to yield the critical Reynolds number for the onset of the periodic flow and the fundamental frequency. However, no information of the base pressure is obtained from the instability analysis. We have no unified theory which can predict the vortex-shedding frequency and the base pressure.

4. SEPARATED FLOW AROUND AXISYMMETRIC AND PLANE-SYMMETRIC BLUFF BODIES

4.1 Spheres and Circular Disks

Wakes of three-dimensional bluff bodies have been studied mostly for axisymmetric bodies such as a sphere and a circular disk normal to the main flow. Large-scale vortices in these nominally axisymmetric wakes appear to be hairpin-like vortices or helical vortices. Details of the vortex structure are obtained at low and moderate Reynolds numbers by flow visualizations and direct numerical simulations. The results will be reviewed, emphasizing unsolved issues.

A global linear stability analysis (Natarajan & Acrivos 1993) shows that periodic vortex shedding from a sphere occurs at Reynolds number (based on the diameter) Re = 277.5 with Strouhal number St = 0.113; the most unstable mode at this Reynolds number is helical (m = 1). The shed vortex is one-sided hairpin vortices which have planar symmetry up to Re = 350-375 (Mittal 1999). The orientation of the hairpin vortices are probably determined by initial conditions or uncontrollable irregularities in the main flow. In this context, it deserves mentioning that, when the main flow is a uniform shear flow with linear velocity profile, the head of the hairpin vortices is always in the direction of high-velocity side (Sakamoto & Haniu 1995). On the other hand, Johnson & Patel's (1999) numerical simulations reveal oppositely oriented hairpin vortices with planar symmetry in the sphere wake. A hairpin vortex is first shed from the recirculating region and then an opposite-sided hairpin vortex is generated downstream of the former by the influence of nearby hairpins and the main flow. It needs explanation that other numerical simulations and flow-visualization experiments have not shown such oppositely oriented hairpin vortices.

At Reynolds numbers higher than Re = 350-375 the angle of shed hairpin vortices changes irregularly from cycle to cycle, the planar symmetry not being maintained. The hairpin vortices are laminar at Re = 500, while they are turbulent at Re = 1,000 (Tomboulides et al. 1993). However, the critical Reynolds number of laminar-to-turbulent transition and the process of the transition have not been studied in detail. Numerical simulations reveal no definite hairpin vortices at $Re = 2.0\times10^4$ (Tomboulides et al. 1993; Kuwahara 1999), because the hairpin vortices are probably obscured by turbulent eddies. No efforts have been made to reveal hairpin vortices at high Reynolds numbers by means of a proper data processing.

The vortical structure at Reynolds numbers greater than $O(10^4)$ is studied only by experiments. Taneda's (1978) flow visualization shows a wavy vortical structure with planar symmetry in the range of $Re = 10^4\text{-}3.8\times10^5$, the plane of symmetry changing slowly and irregularly. This wavy structure suggests the periodic shedding of hairpin vortices but it is not clear whether they are one-sided or not. On the other hand, Berger et al. (1990) found a helical structure at Reynolds numbers less than 10^4 although no mention is made on the helical structure by Taneda (1978). At $Re = 3.8\times10^5\text{-}10^6$ an attached hairpin vortex is formed in the downstream side of a sphere, its legs extending downstream (Taneda 1978). The attached hairpin vortex and the legs are basically steady except for small-scale turbulent eddies, and thus there is no periodic component in the wake. We have no information on vortex structure at $Re > 10^6$. It is a challenge to study the vortical structure in the sphere wake at high Reynolds numbers beyond 10^6.

No theories are available to predict the base pressure at Reynolds numbers at which vortex shedding occurs. An inviscid wake-source model is presented to calculate the pressure on the wetted surface of axisymmetric bodies with the separation point and the base pressure given beforehand (Bearman & Fackrell 1975).

4.2 Elliptic Disks and Rectangular Plates

Wakes of elliptic disks are expected to have properties between those of axisymmetric bluff bodies and two-dimensional ones. Kuo & Baldwin (1967) discovered an unexpected result that far wakes of elliptic disks of aspect ratio of 1.67 and 5.0 have elliptical cross sections, but the major axis of the wake is aligned with the minor axis of the body. This effects was observed in both time-mean velocity and turbulence intensity in the wakes from several minor diameters to distances of 250 minor diameters downstream of the body. They also found a periodic velocity fluctuation in the major plane on top of that in the minor plane. More detailed study on the elliptic wakes is made by Kiya & Abe (1999) to reveal several novel aspects of the elliptic wakes, at Reynolds number $Re = 2.0\times10^4$, based on the minor diameter of the body d. Their results will be discussed in what follows, together with those for wakes of rectangular plates which have basically similar properties as the elliptic wakes (Kiya & Abe 1999).

Velocity contours in the wake in the cross sections normal to the main-flow are elliptic up to approximately (4.0-4.5)d downstream of elliptic disks of aspect ratio of 2.0 and 3.0, the major and minor axes of the wake being aligned with those of the body, respectively. Beyond this position the velocity contours are also elliptic but the major axis of the wake is aligned with the minor axis of the body and *vice versa*. This phenomena is referred to as the axis switching in view of the similar phenomenon found in a jet issuing from an elliptic nozzle (Ho & Gutmark 1987; Hussain & Husain 1989).

The mechanism of the axis switching is completely different in the wake and the jet. In the elliptic jet the axis switching is caused by the self-induced deformation of elliptic vortex loops shed from the nozzle and the merging interaction between neighbouring vortex loops, as demonstrated by Hussain & Husain (1987). In the elliptic wake, however, no elliptic vortex loops are generated along the edge of the disk; rather, hairpin vortices similar to those in the sphere wake are generated near the end of recirculating region in the wake, being alternately shed downstream. The hairpin vortices are oppositely oriented like Karman vortices for cylindrical bodies, and their top is basically in the minor plane of the body. The axis switching occurs because the hairpin vortices moves outwards by the self-induced velocity, increasing the width of the wake in the minor plane. On the other hand, the width of the wake in the major plane decreases due to the in-flow accompanied by the out-flow in the minor plane, by the requirement of continuity, over several minor diameters downstream of the body. The crossover of the widths occurs around x/d = 4.0-4.5, x being the streamwise distance from the body, which is the position of the axis switching.

The alternate shedding of the hairpin vortices generates periodic velocity fluctuations in the minor plane, as first found by Kuo & Baldwin (1967). The vortex-shedding frequency is a function of the aspect ratio of the body. Kiya & Abe (1999) confirmed the existence of another periodic velocity fluctuation in the major plane, which is also mentioned by Kuo & Baldwin (1967). A vortical structure which might be responsible for the periodic component in the major plane has not been revealed yet. Both flow visualizations and direct numerical simulations at a lower Reynolds number of Re = 200 suggest that this periodic component is caused by a meandering motion of the hairpin vortices in the direction of the major axis. The frequency in the major plane is a smooth function of the aspect ratio, so that this frequency is expected to be associated with the intrinsic instability in the near wake. It is not clear whether the meandering motion is also the case at much higher Reynolds numbers.

The frequencies of the periodic components plotted against the aspect ratio are almost the same for the elliptic disks and the rectangular plates at the same Reynolds number. This strongly suggests that the vortex structure in the wake is basically the same for both bodies, despite the existence of sharp corners in the rectangular plates. The periodic components should be attributed to the global instability of the near wake, whose analysis has not been attempted yet. Such an analysis is challenging because unstable modes should be three-dimensional, having two fundamental frequencies and different growth rates around the major and minor planes. It might be possible that the axis switching can be interpreted by the different growth rates.

The oppositely-oriented hairpin vortices in the wake of elliptic disks is expected to change to the one-sided hairpin vortices in the sphere wake at a critical aspect ratio. The transition may give us further insight into the dynamics of wakes of three-dimensional bluff bodies.

5. LOW-FREQUENCY MODULATION IN SEPARATED FLOWS

Periodic vortex shedding occurs in all the flows mentioned above. Amplitudes of velocity and pressure fluctuations associated with the periodic motion appears to experience modulation whose central frequency is much lower than that of the vortex shedding. This modulation is referred to as the low-frequency modulation or unsteadiness, which will be discussed in this section.

5.1 Wakes of Cylindrical Bluff Bodies

The low-frequency behaviour is experimentally observed for normal plates and circular cylinders as bursting in time histories of the lift and drag in a wide range of Reynolds numbers (Roshko 1993; Schewe 1983; Szepessy & Bearman 1992, among others). The low-frequency modulation is also observed in velocity fluctuations in the wake of circular cylinders (Kiya & Ishikawa 1997; Haniu et al. 1995). Intervals of the modulation are an order of magnitude greater than the vortex-shedding period and they are not periodic. Szepessy & Bearman (1992) notes effects of aspect ratio on the modulation time scale. However, it is not evident that the modulation is related entirely to end effects.

In this respect, Najjar & Balachandar's (1998) direct numerical simulations (DNS) are noteworthy. Their simulations are made for the separated flow past a zero-thickness flat plate normal to a free stream at Reynolds number Re = 250, which is based on the height of the plate. The long-time signatures of the drag and lift indicate a low-frequency modulation with a period of approximately 10 times the primary vortex-shedding period. The amplitude and frequency of drag and lift variations during the vortex shedding are strongly modulated by the low-frequency unsteadiness.

A physical interpretation of the low-frequency behaviour is that the flow gradually varies between two different regimes: a regime H of high mean drag and a regime L of low mean drag. In the regime H the shear layer rolls up closer to the plate to form coherent spanwise vortices, while in regime L the shear layer extends farther downstream and the rolled-up Karman vortices are less coherent. In the high-drag regime three-dimensionality is characterized by coherent Karman vortices and reasonably well-organized streamwise vortices connecting the Karman vortices. The results of the simulations strongly suggests that the low-frequency modulation is an *intrinsic* property of nominally two-dimensional wakes of cylindrical bodies.

A mechanism of origin of the low-frequency modulation is not settled yet. Najjar & Balachandar (1998) conjecture that the formation of spanwise and streamwise vortices is not in perfect synchronization, and that the low-frequency modulation is the result of this imbalance or phase mismatch. Large irregularities called vortex dislocations observed in the cylinder wake at Reynolds numbers of a few hundreds (Williamson 1996) are expected to cause modulations of amplitude of velocity fluctuations by the Karman vortices. Moreover, it is not clear whether the modulation of the drag and lift and that of the velocity fluctuations in the wake are caused by the same phenomenon.

5.2 Wakes of Axisymmetric and Plane-symmetric Bluff Bodies

As noted by Roshko (1993), there is a great need to settle the question of possible extraneous effects from end conditions for the low-frequency modulation in nominally two-dimensional flows. In this respect, nominally axisymmetric flows have advantage; they deserve more attention from laboratory and numerical experiments (Roshko 1993). It has been shown that there exists low-frequency modulation in the wake of axisymmetric bluff bodies.

One-sided hairpin vortices are formed in the wake of a sphere to be shed periodically as mentioned in section 3.1. Direct numerical simulations at Re = 500 and 1,000 (Tomboulides et al. 1993) demonstrate the cycle-to-cycle variations in the vortex shedding angle. This cycle-to-cycle variations, which are accompanied by the irregular rotation of the separation point azimuthally around the rear part of the sphere, induces a low incommensurate frequency of approximately 1/4 of the vortex-shedding frequency. The low-frequency component is also observed in Mittal & Najjar's (1999) simulations. Flow-visualization experiments (Taneda 1978, among others) indicate irregular, low-frequency rotation of vortex structures in the sphere wake, but no experimental measurements are made of their typical frequencies.

Berger et al. (1990) observed a low-frequency oscillation in the near wake of a circular disk normal to the main flow at $Re = 1.5\times10^4$ - 3.0×10^5, whose frequency is approximately 1/3 of the vortex shedding frequency. The mode of this low-frequency oscillation appears to be basically axisymmetric (m = 0), and is attributed to a pumping (periodic shrinkage-and-enlargement) motion of the recirculation region. No explanation is made of a mechanism for the pumping motion. The pumping motion has not been reported for the sphere wake.

A low-frequency modulation is reported for the wake of elliptic disks of aspect ratio of 2 and 3 (Kiya & Abe 1999). The modulation is not obvious in the power spectrum of velocity fluctuations in the wake but becomes evident if a wavelet transform is made to the velocity fluctuations. The Morlet wavelet transform has a succession of peaks of modulus of the complex wavelet coefficient $W(a, b)$, where a is the time scale and b is the translation, at the time scale which corresponds to the period of vortex shedding in the minor plane and that of the meandering motion in the major plane. The modulus at the time scale a corresponding to the vortex-shedding period $|W|$ is the convolution of waveform of the real part of the wavelet coefficient. On the other hand, peaks and valleys of the waveform of the real part appears to approximately correspond to peaks and valleys of the original velocity fluctuations. This is approximately so because the original velocity waveforms are contaminated by turbulence components. Thus the power spectrum of the fluctuating component of modulus $|W|'$ is expected to contain information on the low-frequency modulation of amplitude of the periodic component associated with the vortex shedding and the meandering motion.

A broad peak is observed in the power spectrum of modulus in both the major and minor planes; the central frequency of the peak can be interpreted as the representative frequency of the low-frequency modulation. The representative frequency is approximately 1/5 of the vortex-shedding frequency in the minor plane; the same is also the case for the representative frequency of low-frequency modulation of the meandering motion in the major plane. It may be noted that these representative frequencies are of the same order as those for spheres and circular disks. The low-frequency modulation in the elliptic wakes is not an artefact of the wavelet transform. This is supported by its spatial coherence. The spatial coherence is demonstrated by the cross correlation of the fluctuating components of modulus obtained in each plane at opposite positions near the edge of the near wake. The value of the cross correlation is positive at zero time lag, indicating that the low-frequency modulation is statistically in phase in each plane. On the other hand, the cross correlation of $|W|'$ at the edges of the near wake in the different planes is negative at zero time lag; thus the low-frequency modulation is statistically out of phase in the different planes. The above results suggest that, when the wake is in the phase of enlargement in the major plane, the wake in the minor plane is in the phase of shrinkage, and *vice versa*. The same result is obtained in a range of 2.0-8.0 minor diameters downstream of the body, so that the low-frequency modulation is of large length scale. Changes of vortical structure in the wake associated with the low-frequency modulation are to be studied to elucidate a mechanism which is responsible for the modulation.

5.3 Separated-and-Reattaching Flows

Low-frequency modulation is also observed in nominally two-dimensional and axisymmetric separated-and-reattaching flows: backward-facing step flows; leading-edge separation bubbles of blunt plates and blunt circular cylinders. The modulation in these flows is sometimes referred to as flapping because it is accompanied by a transverse oscillation of the separated shear layer. The flapping motion has been found in the power spectra of surface-pressure fluctuations and velocity fluctuations in the separation zone. The central frequency of the flapping motion is of the order of 1/5-1/6 of the vortex shedding frequency, being of the same order as that for the three-dimensional wakes. The flapping motion is an intrinsic property of the separation bubbles, not being due to extraneous effects from end effects. This is supported by the fact that the flapping is found in the leading-edge separation bubble of a blunt circular cylinder, in which no end effects are included.

The mechanism of the flapping motion is conjectured as follows. Eaton & Johnston (1982) suggest that this is caused by an instantaneous imbalance between the entrainment from the recirculation zone and the reinjection of fluid from the reattachment region. An unusual event causes a short-time breakdown of the spanwise vortices in the separated shear layer, which would temporarily reduce entrainment rate and thereby cause an increase in the volume of recirculating fluid. This increase will move the shear layer away from the surface and increase the short-time averaged reattachment length. This enlargement-and-shrinkage motion of the separation bubble is confirmed by a conditional-sampling technique (Kiya & Sasaki 1985). The mechanisms proposed by Cherry et al. (1984) and Driver et al. (1987) are more or less similar to the above one if 'a short-time breakdown of the spanwise vortices' in Eaton & Johnston (1982) is replaced by 'a temporary interruption to shear-layer growth/coalescence process' in Cherry et al. (1984) and by 'a disorder of roll-up and pairing process' in Driver et al. (1987). The pseudo-periodic nature of the flapping motion seems to be inconsistent with the assumption that an unusual event causes the breakdown of the spanwise vortices, suggesting a deterministic mechanism. Flow visualizations and spatio-temporal measurements of vortical structures associated with the flapping motion are needed to find more detailed properties and the mechanism of the flapping motion.

6. ACTIVE CONTROL OF UNSTEADY SEPARATED FLOWS

Flow separation from a solid surface should be avoided in most of engineering applications; when the separation is unavoidable, its spatial extent and unsteadiness should be reduced as much as possible. Attempts have been made to realize this by an active control. As a prototype of unsteady separated flows, we consider the flow around an aerofoil undergoing an irregular pitching motion of sufficiently large amplitudes. Similar unsteady separation appears when the direction of approaching flow changes randomly such as in wind-turbine blades. We want to suppress the separation or to reduce the separation zone as small as possible at all phases of the pitching motion by an interactive control system in which a precursor of large-scale separation, if it exists, is detected to operate an actuator. A number of challenging issues have to be overcome to realize this interactive control.

One of such issues is whether the precursor really exists or not. An experiment on an aerofoil undergoing a pitching-up motion with a constant angular velocity indicates the existence of a precursor in velocity and surface-pressure time histories (Mochizuki et al. 1999). The detection of the precursor determines the timing of operation of the actuator to suppress the otherwise large-scale separation. A wide margin of time between the detection of the precursor and the operation of the actuator is crucial for the effective control.

The development of actuators is another challenging issue. The actuator should sufficiently be small and have a short response time and sufficient power to prevent large-scale separation. The synthetic-jet actuator (Smith & Glezer 1997) is a promising candidate for such an actuator. The function of this actuator is akin to that of blowing from a slot on the surface of the body.

In what follows, an introduction will be made on a few researches in the authors's laboratory towards the above-mentioned issues.

6.1 Precursor of Separation

A NACA0015 airfoil undergoes a pitch-up motion from attack angle $a(t) = 0^o$ to 30^o about its quarter-chord position with a constant pitch rate *w*. The non-dimensional pitch rate $S = wc/(2U)$, where U is the main-flow velocity and c is chord, is 0.012. Reynolds number based on chord is 4.0×10^4. The instantaneous surface pressure is measured at various positions in the mid-span plane on the suction side. Preliminary measurements indicated that the separation starts from the trailing edge, moving upstream with increasing angle of attack.

The surface pressure fluctuations at a fixed point are found to have a part of a sinusoidal waveform with growing amplitude before a high-frequency and large-amplitude fluctuation which means the large-scale separation. The sinusoidal waveform appears to start approximately at $2.0c/U$ before the signal of separation at the position $0.45c$ downstream of the leading edge. A wavelet analysis of this signal shows that the frequency of the sinusoidal wave is approximately $10.0U/c$. The growth of the amplitude before separation is approximately exponential.

This sinusoidal wave can be interpreted as a precursor of separation on the basis of the following reason. Just before separation a velocity profile with an inflection point appears at the point of observation. A linear inviscid stability analysis of such a flow is made by Michalke (1990), showing that the fundamental frequency of instability is a function of the distance between the inflection point and the surface. This theory predicts the fundamental frequency of $7.0U/c$ for the measured velocity profile, which is of the same order as that of the experiment. The difference is conjectured to be partly attributed to effects of the longitudinal pressure gradient due to the surface curvature in the experiment, which are not included in the theory.

Does the precursor exist at higher pitch rate S or in other type of unsteady separated flows? How is the effects of Reynolds number? These are challenging issues to be tackled in the future.

6.2 Optimum Timing of Operation of an Actuator

An important issue is the margin of time from the detection of the precursor to the onset of separation. Mochizuki et al. (1999) studied an optimum timing of dynamic-stall control of a pitching-up aerofoil by means of a wall jet along the suction surface. The timing is optimum in the sense that the energy of the jet required to suppress the dynamic stall is minimum. In their experiment a NACA0020 aerofoil of chord c undergoes a pitching-up motion from $a(t) = 0^o$ to 30^o with a constant angular velocity about its quarter-chord position in the main flow of velocity U. The non-dimensional pitching rate S is in a range of 0.008-0.023. Reynolds number based on the chord is 9.0×10^4. A thin slot of width $b = 0.004c$ is located at a position of $0.04c$ from the leading edge to issue the wall jet of velocity V_j for control. The timing of start of the jet was controlled by a computer-regulated proportional valve. Without the control the large-scale separation is observed at a time when the angle of attack reaches to $\alpha = 28^o$. The origin of time $t = 0$ is taken at this instant.

When the time of start of the control jet is fixed at t_s (< 0), the large-scale separation is suppressed for a velocity V_j greater than a critical value V_{jc}. This critical value is fairly constant $V_{jc}/U = 3.1$ in the range of $Ut_s/c < -5.5$ but rapidly increases as the time Ut_s/c tends to 0. In view of energy of the jet needed to suppress the separation it is undesirable to start the jet too early because the longer the time of issuing, the larger is the total energy. The total energy E defined by

$$E = \int_{t_s}^{t_e} (1/2) r V_j^2 bl V_j \, dt$$

where t_e is the time when the pitching-up motion is over, attains a significant minimum at Ut_s/c = -6.0. The minimum energy is approximately 10% of the energy of the main flow, which is the value of E with V_j replaced by the main-flow velocity U. This optimum timing is fairly independent of the pitching rate in a range S = 0.008-0.023.

The experiment described in Section 5.1 shows that the instant at which the precursor is detected on the surface-pressure fluctuation is approximately Ut/c = -2.0 at the position of 0.42c downstream of the leading edge for S = 0.012. Unfortunately this happens to be later than the optimum timing Ut_s/c = -6.0. A different precursor or criterion is needed for an interactive control of the unsteady separation.

6.3 Separation Control by a Chain of Vortex Rings

The separated shear layer of a stalled aerofoil rolls up to form a chain of spanwise vortices. If a vortex ring or a vortex pair is introduced into the shear layer, the interaction between the shear-layer vortices and the external vortices is expected to generate larger scale of vortices than those in the original shear layer (Kiya et al. 1986; Kiya et al. 1999). These studies suggest that the entrainment rate of the shear layer can be enhanced by the vortex interaction, and thus the reduction in the separation zone.

Experiments are made to bombard the rolling-up vortices in the shear layer of a stalled flat-plate aerofoil by vortex rings to examine to what extent the vortex interaction is effective in reducing the separation zone, thus reducing the drag and increasing the lift (Kiya et al. 1999). Vortex rings of the same size and circulation are successively introduced into the shear layer near the leading edge with frequency F. The interaction is found to produce a compact rolling-up vortex just downstream of the leading edge to reduce the size of the separation zone.

The effectiveness of the vortex interaction on the reduction of the separation zone can be measured by a change in the momentum defect in the near wake M, which is a good measure of drag acting on the aerofoil. The momentum defect is a function of the frequency F and the circulation of the vortex ring G. The reduction in the momentum defect amounts to approximately 20% of M of the base flow for the frequency of Fc/U > 4.0. The momentum defect attains a broad minimum at the frequency of Fc/U = 4.0. This value remains the same when the main-flow velocity is increased by the factor of 2.

The reason why M attains a minimum at a particular frequency Fc/U = 4.0 can be interpreted as follows. Periodic forcing of stalled flow around aerofoils by acoustic waves and oscillating jets, yields a maximum lift at a particular forcing frequency, F_p. The drag is expected to attain a minimum at the same frequency because the height of the separation zone is reduced to the maximum extent. The frequency normalized in the form $F_p c/U$ is in a range of 3-4 (Zaman & McKinzie 1991; Zaman 1992), 1-3 (Hsiao et al. 1989), and 2 (Bar-Sever 1989), being of the same order as the optimum frequency Fc/U = 4.0. Thus the reason is likely to enhance the shedding- type instability or impinging-type instability mentioned in section 2.

The momentum defect decreases with increasing circulation of the vortex rings to become fairly constant at values of G greater than roughly $G/(Uc)$ = 0.3. This is probably because such vortex rings pass through the separated shear layer, leaving more or less the same effects on the shear-layer vortices, as suggested by the two-dimensional numerical simulation of a vortex pair interacting with shear-layer vortices (Kiya et al. 1999). The value $G/(Uc)$ = 0.3 is approximately 1.5 times the circulation of the shear-layer vortices which interact with the vortex rings. A three-dimensional simulation on the interaction between a vortex ring and a rectilinear vortex tube suggests that the critical value of the vortex ring is approximately 1.5 times that of the vortex tube.

Loss of power by the drag acting on the aerofoil is the drag multiplied by the main-flow velocity. The drag is reduced by the impinging vortex rings; this reduction corresponds to the reduction in loss of power DW. An efficiency of the control can be evaluated by $h = DW/W_{vr}$, where W_{vr} is the power required to generate the vortex rings. The efficiency attains a broad maximum at $Fc/U \approx 4.0$ for a fixed value of G, which is the fundamental frequency of the shedding-type or impinging-type instability. This implies that the steady round jet , which corresponds to $Fc/U = \infty$, is not the best choice for the separation control in terms of the efficiency. Moreover, the efficiency attains a maximum at a particular value of circulation $G/(Uc) \approx 0.32$. This value is approximately the same as that beyond which the momentum defect becomes independent of the circulation.

7. CONCLUDING REMARKS

Challenging issues on separated flows have been discussed for several prototype flows. Flow structure in the prototype flows have been studied for many years by experiments and, especially in recent years, numerical simulations. Particle-image velocimetry yields three-dimensional fields of velocity and vorticity vectors almost the same extent as direct numerical simulations. These are experimental results, whose acquisition and processing have been made efficient and economical by the advent of computers and laser-applied technology. What is lacking is a physical model which can predict essential properties of the separated flows, especially the base pressure. This is because the base pressure, for example, is determined by the overall dynamics of the near wake flows. It may be emphasized that we have no theories to predict the drag coefficient of such a simple shape as a circular cylinder or a sphere as a function of Reynolds number in the range of the vortex shedding. Such a theory, if it had been constructed, will lead to new understanding of separated flows and to a new way of looking at them. The mechanism of low-frequency modulation of vortex shedding is not resolved yet.

In order to understand those separated flows encountered in engineering applications which have multiple parameters, we need to add other parameters to the prototype separated flows. An elliptic disk is an example of such an extension of a circular disk to study effects of another length scale on the wake. The additional parameters, if they are properly chosen, may yield novel features which will enhance researches in the future.

Control of flow to suppress the large-scale separation or to reduce the separation zone has wide potential applications in fluids engineering because the control reduces the drag, flow unsteadiness and aerodynamic sound. Passive control is not effective once large-scale separation has occurred, this being the reason why active control is required. One of challenging issues in the active control of large-scale separation is a large energy to be supplied to the actuators. Large-scale separation in turbomachinery and air-crafts comes into problem in unusual and emergent situations, so that a high energy for control may be permissible although it is not undesirable. Whether there exists a precursor of large-scale separation is still an open question.

REFERENCES

Asai, M, Nakagawa, H. and Nishioka, M. (1996). "Wake instability and frequency selection of the von Karman vortex shedding", Journal of Japan Society of Aeronautical and Space Sciences, 44, 251-256 (in Japanese).

Bar-Sever, A. (1989). "Separation control on an airfoil by periodic forcing", AIAA Journal 27, 820-821.

Bearman, P.W. and Fackrell, J.E. (1975). "Calculation of two-dimensional and axisymmetric bluff-body potential flow", Journal of Fluid Mechanics, 72, 229-241.

Berger, E., Scholz, D. and Schumm, M. (1990). "Coherent vortex structures in the wake of a sphere and a circular disk at rest and under forced vibrations", Journal of Fluids and Structures, 4, 231-257.

Cherry, N.J., Hillier, R. and Latour, M.E.M.P. (1984). "Unsteady measurements in a separated and reattaching flow", Journal of Fluid Mechanics, 144, 13-46.

Driver, D.M., Seegmiller, H. and Marvin, J.G. (1987). "Time dependent behavior of a reattaching shear layer", AIAA Journal, 25, 914-919.

Eaton, J.K. and Johnston, J.P. (1982). "Low-frequency unsteadiness of a reattaching turbulent shear flow", Turbulent Shear Flows 3 (Eds. L.J.S. Bradbury, F. Durst, B.E. Launder, F.W. Schmidt and J.H. Whitelaw), 162-170, Springer-Verlag, Berlin.

Haniu, H., Sakamoto, H., Nakamura, J. and Obata, Y. (1995). "Long time scale fluctuation in the irregularity of vortex shedding: Spectral analysis of the local rms values and circulation)", Transactions of Japan Society of

Mechanical Engineers, 61, 379-387 (in Japanese).

Hsiao, F., Liu, C., Shyu, J. and Wang, M. (1989). "Control of wall-separated flow by internal acoustic excitation", AIAA Paper 89-0974.

Ho, C.M. and Gutmark, E. (1987). "Vortex induction and mass entrainment in a small-aspect-ratio elliptic jet", Journal of Fluid Mechanics, 179, 383-405.

Huerre, P. and Monkewitz, P.A. (1990). "Local and global instabilities in spatially developing flows", Annual Review of Fluid Mechanics, 22, 473-537.

Hussain, F. and Husain, H.S. (1989). "Elliptic jets. Part 1. Characteristics of unexcited and excited jets", Journal of Fluid Mechanics, 208, 257-320.

Johnson, T.A. and Patel, V.C. (1999). "Flow past a sphere up to a Reynolds number of 300", Journal of Fluid Mechanics, 378, 19-70.

Kiya, M. and Abe, Y. (1999). "Turbulent elliptic wakes", Journal of Fluids and Structures, 13, 1041-1067.

Kiya, M. and Ishikawa. H. (1997). "Coherent structures and large low-frequency irregularity in free turbulent shear flows educed by wavelet transform and proper orthogonal decomposition", Proceedings of 2nd China-Japan Workshop on Turbulent Flows (Ed. Qing-Ding Wei), 8-22, State Key Laboratory for Turbulence Research, Peking University, Peking.

Kiya, M., Mochizuki, O. and Suzuki, N. (1999). "Separation Control by Vortex projectiles", AIAA Paper 99-3400.

Kiya, M., Ohyama, M. and Hunt, J.C.R. (1986). "Vortex pairs and rings interacting with shear-layer vortices", Journal of Fluid Mechanics, 172, 1-15.

Kiya, M., Shimizu, M, and Mochizuki, O. (1997). "Sinusoidal forcing of a turbulent separation bubble", Journal of Fluid Mechanics, 342, 119-139.

Kiya, M., Takeo, H., Mochizuki, O. and Kudo, D. (1999). "Simulating vortex pairs interacting with mixing-layer vortices", Fluid Dynamics Research, 24, 61-79.

Kuo, Y.-H. and Baldwin, L.V. (1967). "The formation of elliptic wakes", Journal of Fluid Mechanics, 27, 353-360.

Kuwahara, K. (1990). "Unsteady flow simulation and its visualization", AIAA Paper 99-3405.

Michalke, A. (1991). "On the instability of wall-boundary layers close to separation", Separated Flows and Jets, IUTAM Symposium Novosibirsk /USSR 1990 (Eds. V.V. Kozlov and A.V. Dovgal), 557-564, Springer- Verlag, Berlin.

Mittal, R. (1999). "Planar symmetry in the unsteady wake of a sphere", AIAA Journal 37, 388-390.

Mittal, R. and Najjar, F.M. (1999). "Vortex dynamics in the sphere wake", AIAA Paper 99-3806.

Mochizuki, O., Kiya, M. and Kumano, S. (1999). "Reactive control of unsteady separation", Proceedings of the Eighth Asian Congress of Fluid Mechanics, December 6-10, 1999, Shenzhen, China (Eds. L. He, Y. Tang and D. Zhao), The Chinese Society of Theoretical and Applied Mechanics, Beijing.

Mochizuki, M., Kiya, M. and Kurohata, K. (1999). "Precursor of separation", Journal of Japan Society of Fluid Mechanics, 18, 391-393 (in Japanese).

Najjar, F.M. and Bachandar, S. (1998). "Low-frequency unsteadiness in the wake of a normal plate", Journal of Fluid

Mechanics, 370, 101-147.

Nakamura, Y. and Nakashima, M. (1986). "Vortex excitation of prisms with elongated rectangular H and |? cross sections", Journal of Fluid Mechanics, 163, 149-169.

Natarajan, R. and Acrivos, A. (1993). "The instability of the steady flow past spheres and disks", Journal of Fluid Mechanics, 254, 323-344.

Roshko, A. (1993). "Perspectives on bluff body aerodynamics", Journal of Wind Engineering and Industrial Aerodynamics, 49, 101-120.

Sakamoto, H. and Haniu, H. (1995). "The formation mechanism and shedding frequency of vortices from a sphere in uniform shear flow", Journal of Fluid Mechanics, 287, 151-171.

Sasaki, K. and Kiya, M. (1991). "Three-dimensional vortex structure in a leading-edge separation bubble at moderate Reynolds numbers", ASME Journal of Fluids Engineering, 113, 405-410.

Sigurdson, L.W. (1995). "The structure and control of turbulent reattaching flow", Journal of Fluid Mechanics, 248, 267-296.

Smith, F.T. (1979). "Laminar flow of an incompressible fluid past a bluff body: the separation, reattachment, eddy properties and drag", Journal of Fluid Mechanics, 92, 171-205.

Smith, B.L. and Glezer, A. (1997). "Vectoring and small-scale motions effected in free shear flows using synthetic jet actuators", AIAA Paper 97-0213.

Schewe, G. (1983). "On the force fluctuations acting on a circular cylinder in cross flow from subcritical up to transcritical Reynolds numbers", Journal of Fluid Mechanics, 133, 265-285.

Sychev, V.V., Ruban, A.I., Sychev, V.V. and Korolev (1998). Asymptotic Theory of Separated Flows, Cambridge University Press, Cambridge.

Szepessy, S. and Bearman, P.W. (1992). "Aspect ratio and end plate effects on vortex shedding from a circular cylinder", Journal of Fluid Mechanics, 234, 191-217.

Taneda, S. (1978). "Visual observations of the flow past a sphere at Reynolds numbers between 104 and 106", Journal of Fluid Mechanics, 85, 187-192.

Tomboulides, A.G., Orzag, S.A. and Karniadakis, G.E. (1993). "Direct and large-eddy simulation of axisymmetric wakes", AIAA Paper 93-0546.

Williamson, C.H.K. (1996). "Vortex dynamics in the cylinder wake". Annual Review of Fluid Mechanics, 28, 477-539.

Zaman, K.B.M.Q. (1992). "Effect of acoustic excitation on stalled flows over an airfoil", AIAA Journal, 30, 1492-1499.

Zaman, K.B.M.Q. and McKinzie, D.J. (1991). "Control of laminar separation over airfoils by acoustic excitation", AIAA Journal, 29, 1075-1083.

Zdravkovich, M.M. (1997). Flow Around Circular Cylinders, Oxford University Press, Oxford.