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Edited by Helmut Z. Baumert, John Simpson and Jurgen Sundermann
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PART I

On the physics of turbulence

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Editor of Part I

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1 Prologue

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In mathematics you don't understand things.
You just get used to them.
Johann von Neumann, 1903–1957

In contrast to the engineer who deals mostly with non-stratified flows of limited Reynolds number but other specific challenges, turbulence studied by oceanographers is influenced by stratification (and thus by internal waves) and by extremely high Reynolds numbers.

Part I of the book begins with a sketch of the physical nature of turbulence (Chapter 2), continues with new descriptions for stratified conditions (Chapters 3–6), and is completed by accounts of intermittency (Chapter 7) and horizontal mixing processes (Chapter 8). For the many other aspects of turbulence and its theory the reader is referred to classical textbooks (Batchelor, 1960, 1967; Monin and Yaglom, 1967; Rotta, 1972; Tennekes and Lumley, 1976; Hinze, 1975; Monin and Yaglom, 1975; Lesieur, 1997; Pope, 2000).

Chapter 3 presents a new two-equation closure for energy and enstrophy in homogeneously stratified shear layers and the collapse of turbulence into internal waves. Chapter 4 applies this closure to spatially inhomogeneous conditions and predicts the Monin–Obukhov similarity scaling correctly.

The dichotomy of continuity and discontinuity has a long history. We can describe the strange dual nature of light only with both the continuous field concept and the discontinuous particle concept. In theoretical fluid dynamics, the past was governed by continuous images (the Navier–Stokes or NS equation and its relatives). Discrete-particle concepts for fluid motions were developed only for computational purposes (Boltzmann-lattice, lattice-gas, and random-vortex methods; for references see e.g. Lesieur, 1997).

In particular, theories of turbulence were more or less exclusively gained from Friedman–Keller expansions of the NS equations, averaging, and use of closure hypotheses based on observations, symmetry, and heuristic arguments. This approach has led to increasing numbers of "universal" closure parameters in models of increasing complexity, as illustrated for instance by the work of Canuto *et al.* (2001). For marine applications, Burchard (2002b) has given an account of this NS-based approach.

A counterpart of the continuous concept, i.e. the image of high-*Re* turbulence as a (large) ensemble of discrete elementary vortex structures, is presented in Chapter 5 – to the best of our knowledge, for the first time. It gives simple though powerful equations for energy and enstrophy, but is not able to predict spectral characteristics. The complementary spectral description is derived systematically from first principles in Chapter 6 – for the stratified case; to the best of our knowledge, for the first time, too. It is based on the continuous NS equation and uses a successive, RNG-related scale-elimination technique.

The new results are completed by reviews of two other fundamental aspects of turbulence: intermittency (Chapter 7) and horizontal mixing (Chapter 8). Chapter 7 presents log-normal, log-gamma, log-Poisson, and log-Lévy models for the intermittency of turbulence. Chapter 8 includes an overview on phenomenology and empirical relations for the poorly understood mixing processes in the surface plane of an ocean where non-coherent surface waves and horizontal eddies act simultaneously (Section 8.2) and the theory of this process (Section 8.3), which is based on stochastic calculus and spectral wave properties. It gives a novel derivation of the coefficient of horizontal particle separation, which was first found for the atmosphere by Richardson (1926) and for the sea surface by Richardson and Stommel (1948).

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2 Turbulence: its origins and structure

JOEL FERZIGER

2.1 Introduction: the nature of turbulence

It is difficult even for expert researchers to agree on a definition of turbulence. Required elements that are generally agreed upon include the following.

- **Three-dimensionality.** The flow may be two-dimensional in the mean, but turbulent flows, at least all the ones of interest to geophysicists and engineers, are always fully three-dimensional. Two-dimensional turbulence exists, but is a very different phenomenon; it is relevant to the large scales of geophysical flows but, even in those flows, the smallest scales are three-dimensional. We shall say something about two-dimensional turbulence below, since understanding it is important and relevant to understanding turbulence in general.
- **Unsteadiness.** A turbulent flow may be steady in some statistical mean sense, but turbulent flows are always highly unsteady. They are also characterized by a wide range of time scales on which fluctuations occur (see below).
- **Strong vorticity.** Almost all flows contain some vorticity, but in turbulent flows there are regions of strong coherent vorticity and other regions containing little vorticity; it is the fluctuations of the vorticity that are important. The process of vortex stretching is essential to three-dimensional turbulence.
- **Unpredictability.** Turbulent flows are characterized by the property that two flows whose present states differ only slightly will develop so that the differences increase exponentially with time. At some much later time, it will be essentially impossible to recognize that the two flows originated from nearly identical states. However, the statistical properties of the flows will remain nearly indistinguishable.
- **Broad spectrum.** We have already noted that turbulent flows fluctuate on a broad range of time scales. They also contain fluctuations on a wide range of length scales; furthermore, the range of scales increases with the Reynolds number.

Beyond these properties on which most people agree, it is difficult to say much that is very general. Most people would agree that turbulent flows are highly random and/or noisy; the term chaotic could be used, but it has been given a more restricted meaning in recent years.

However, there is more to turbulence than randomness. It is generally agreed that coherent structures exist in nearly all turbulent flows; one needs to be careful with the term "coherent structure" because, despite considerable discussion, an agreed definition of this term does not yet exist. There is, however, general agreement that they are important. Although coherent structures probably account for only a small fraction of the turbulence energy (the fraction is probably dependent on the flow and the parameters that characterize it), they are apparently responsible for more than their fair share of the transport of properties such as species, mass, momentum, and energy. The coherent structures of a particular flow are similar in form but far from identical and they do not appear regularly either in time or in space. It is this lack of regularity that makes them so difficult to define and describe. The largest part of the turbulence energy is apparently due to truly random motion (which may be the remains of old coherent structures) and is probably responsible for much of the irregularity of the coherent structures.

This picture helps explain why turbulence is such a difficult problem. If it were completely random, statistical methods would probably have solved the problem long ago. If it were purely deterministic, computer simulation might have solved the problem by now. In fact, turbulence is sufficiently incoherent that the signal-to-noise ratio of the coherent structures is very low; at the same time, the lack of a clear definition of a coherent structure and the variation in the size, duration, and time of occurrence makes their eduction from the noisy data nearly impossible. Indeed, this is one of the most difficult problems in signal processing.

When we add to this picture the probability that the coherent structures are different in each flow, we see that the likelihood of finding a simple method for predicting all flows (other than solving the Navier–Stokes equations via direct numerical simulation) is exceedingly small. The search for a single universal method capable of predicting all turbulent flows has gone on for a long time and, although it has produced many useful results, it is still far from the ultimate goal.

It should be noted that, because turbulence is so far from being completely understood, there is a wide range of ideas on what it is and on its kinematics and dynamics. Every researcher has his or her own ideas based on experience and heated discussions often arise when the subject

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is discussed. In this author's opinion, almost everyone has some part of the "truth." Indeed, it is not uncommon for people to state similar ideas or describe the same phenomenon in different ways. The lack of agreement may confuse someone new to the subject, so it is wise to read several viewpoints and form one's own opinion. These remarks certainly apply to the ideas in this chapter!

2.2 Laminar–turbulent transition

2.2.1 *Linear stability theory*

To understand the physics of turbulence in depth, it is important to look at the origins of turbulence. Almost all turbulence begins in the process of transition from laminar to turbulent flow. These processes have been studied for a long time and a great deal of progress in understanding them has been achieved by a combination of experiments, simulations, and theory. There is, however, still a great deal more to learn. It is worth reviewing some of what is known about transition because turbulence retains many of the characteristics of the transition process that created it and because transition is often easier to understand.

The most fundamental theoretical tool of transition studies is linear perturbation theory. In this approach, one assumes that an initially laminar flow (which is itself a solution to the Navier–Stokes equations) is modified by a weak disturbance and asks whether the disturbance will be amplified. Since the disturbance is weak, the Navier–Stokes equations may be linearized about the laminar solution to produce a linear set of equations for the disturbance. It is further assumed that, after the initial introduction of the perturbation, there is no further forcing of the flow; the perturbation must grow on its own or die out.

Since there is no forcing, the equations for the perturbation are linear and homogeneous in the disturbance (the difference between the actual state of the flow and the original laminar state). Furthermore, the boundary conditions are not modified by the perturbation, so the boundary conditions on the latter are also homogeneous. Given these properties, and further assuming that the laminar flow can be treated as a parallel flow, one can assume that the solution has a separable form with a time dependence that is exponential. The result is an eigenvalue problem in the spatial coordinates. The problem is then to determine whether the solution grows in time; this depends on the sign of the real part of the eigenvalue. (In some versions of the theory, one must look at the imaginary part of the eigenvalue, but that is due to the use of a different convention for naming the eigenvalue.) One can also ask whether the perturbation grows with downstream distance, but this is usually a more difficult problem.

There is no intent to review linear stability theory in detail here. The interested reader should consult the works by Drazin and Reid (1981) and Betchov and Criminale (1967) for excellent introductions to the subject. We merely mention a few significant points. In many flows, the mechanism of instability is essentially inviscid, i.e. instability occurs even when the effects of viscosity are ignored. In such a flow, the growth rate of the disturbance usually decreases when the effects of viscosity are taken into account. There are other flows (an important example is given below) in which viscosity plays an essential role in the instability. The inviscid linear perturbation equation is called the Rayleigh equation and is of second order in the spatial coordinates. When viscosity is included, the equation becomes of fourth order in space and is called the Orr–Sommerfeld equation.

2.2.2 *Primary instability of free shear flows*

The simplest instability to analyze (and the first to be studied historically) is the instability of the mixing layer, a region between two fluid layers of differing speeds. A typical velocity profile is shown in Fig. 2.1. This type of flow is inviscidly unstable if the velocity profile contains an inflection point or, which is the same thing, a maximum of the vorticity. The mixing layer rolls up into discrete vortices whose separation is a few times the thickness of the laminar layer. This is the famous Kelvin–Helmholtz instability. It can be understood via a number of physical arguments. The rolled-up state is shown in Fig. 2.2. It is important to note that this mechanism produces intense vortices that play an important role in what happens later, including the turbulent state. The instability favors the growth of vortices that are perpendicular to the main flow, although slightly skewed vortices can be produced under certain conditions. The two-dimensional array of vortices may be viewed as a kind of two-dimensional turbulence.

In general, however, the layer produced by this roll-up process does not have the same form as a two-dimensional array in which all of the vorticity is

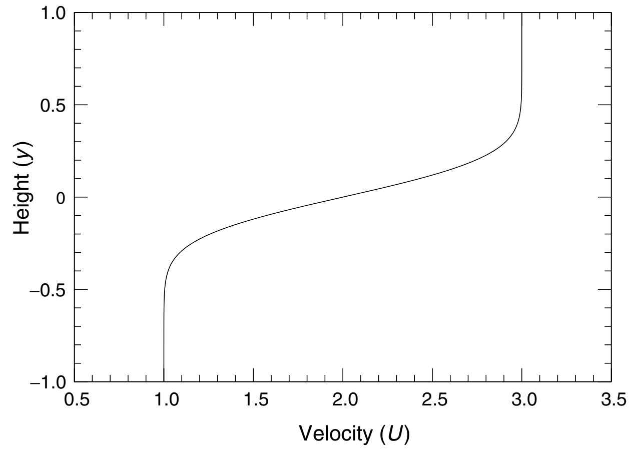

Fig. 2.1. A typical mixing layer profile.

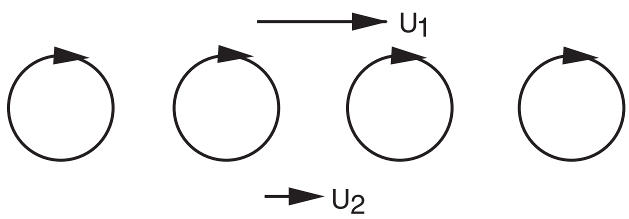

Fig. 2.2. The result of Kelvin–Helmholtz instability. The mixing layer has rolled-up into a line of intense two-dimensional vortices.

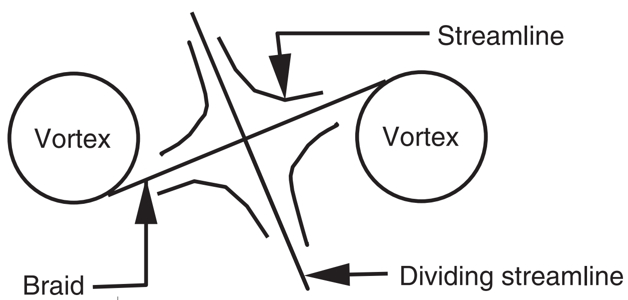

Fig. 2.3. The detailed structure of a portion of the rolled-up mixing layer.

concentrated in small, nearly circular, regions surrounded by regions nearly devoid of vorticity. Some of the vorticity remains outside the vortices and there is an inflow into the vortices through the braid region as shown in Fig. 2.3. Also, except at low Reynolds number, the distribution of vorticity within the rolled-up vortices is not uniform. As we shall see, this structure may affect the dynamics of what happens later in important ways.

When the flow has a velocity profile that is not monotonic, such as in a jet or a wake, the instability mechanism is similar to what is observed in the mixing layer but a little more complicated. A velocity profile of the laminar flow is shown in Fig. 2.4. In this case, the instability produces roll-up of the two sides of the flow separately. (Generally, vorticity of each sign tends to agglomerate into concentrated vortices, whereas vorticity of opposite sign tends to segregate.) These roll-ups are similar to that observed in the mixing layer (see above), but the interesting new feature is that the instability tends to cause the vortices in the two layers to be staggered with respect to each other. This arrangement is known as the von Kármán vortex street and has been observed in the atmosphere and the ocean as well as in the laboratory. It is illustrated in Fig. 2.5.

These are the most important instability mechanisms that operate in simple free shear flows. More complex laminar flows produce more complex rolled-up states and there are important examples of such flows. Of special importance is what happens when the initial state of the flow is three-dimensional or additional strains such as rotation and curvature act on the flow. The result is almost always a flow more complex than the ones described above; these flows contain discrete vortices of more complex structure than those illustrated in the figures. These flows tend to become fully turbulent much more readily than do the ones shown above. This will be discussed later.

As we have already seen, in clean low-Reynolds-number flows, the roll-up process tends to be quite regular and proceeds more or less as illustrated above. After the roll-up has been completed, several processes that increase the complexity of the flow may occur. It is possible for the flow to remain two-dimensional. However, any irregularity of the vortex array (deviation from perfect alignment, variation in the separation or strength of the vortices) can cause interactions among the vortices that increase the complexity of the flow and the rate of growth of its thickness. Probably the most important of these is a process of agglomeration that usually occurs between pairs of vortices and leads to an increase in vortex size and a decrease in number of vortices. This process, which is usually called pairing, is illustrated in Fig. 2.6 and was first described by Brown and Roshko (1974).

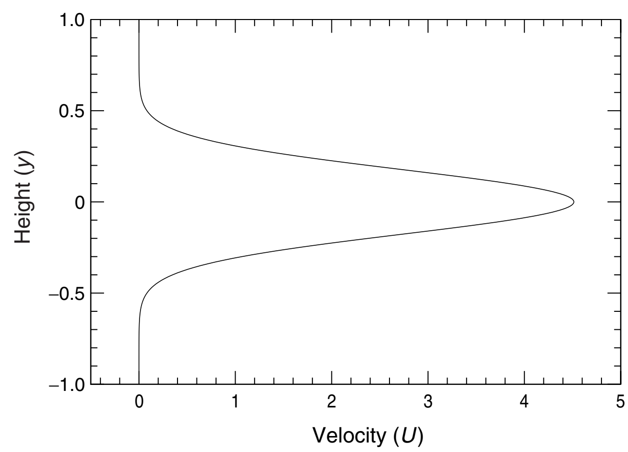

Fig. 2.4. A typical profile of a laminar jet.

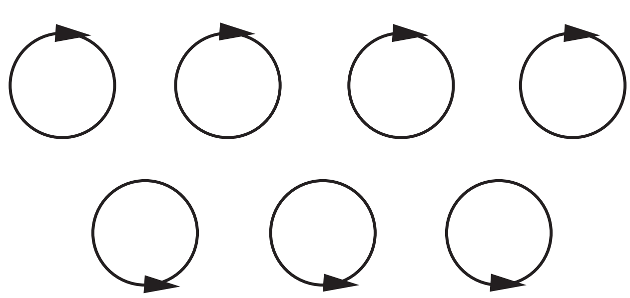

Fig. 2.5. The result of instability in a jet. The instability produces a set of staggered two-dimensional vortices called a von Kármán street.

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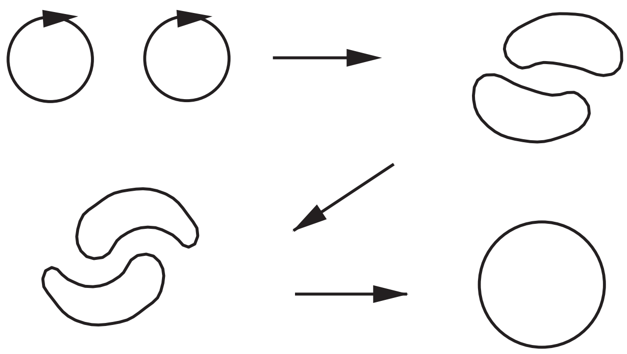

Fig. 2.6. An illustration of vortex pairing.

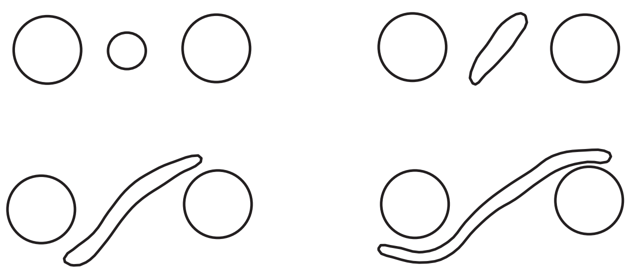

Fig. 2.7. An illustration of vortex tearing.

Other related processes include ones in which more than two vortices combine to form still larger vortices. In general, this process occurs only when the flow is carefully controlled and prepared. An alternative is the process of "tearing" in which one small vortex located between two larger ones is torn apart and its vorticity is redistributed to its larger neighbors. This process was first described by Moore and Saffman (1975) and is illustrated in Fig. 2.7.

2.2.3 *Later stages of transition in free shear flows*

We saw earlier that instability of free shear flows of simple structure tends to produce a flow containing large two-dimensional vortices. These states strongly resemble the two-dimensional turbulence that was mentioned in the preceding section and will be discussed further later. Unless the flow is carefully prepared, it does not remain in a two-dimensional state for very long. Under laboratory conditions or in a carefully controlled numerical simulation, the process of transition to a three-dimensional state may occur in a relatively orderly fashion, but, in highly perturbed flows, the process may be much more irregular. Several mechanisms that can operate at this stage of the development of the flow have been described; each has been proposed as the sole mechanism for transition, but it is likely that each mechanism is active and plays some role in the development. It is also likely that different mechanisms are really only different ways of describing the same physics.

As we noted, after the roll-up process created by Kelvin–Helmholtz instability, some vorticity remains between the vortices; it may become subject to a secondary instability. This may take several forms. One possibility was described by Lin and Corcos (1984). In this process, which can be called a secondary instability, the vorticity in the "braid" region between the discrete vortices is strained by the vortices and undergoes an instability that stretches it into longitudinal vortices that are aligned with the flow. This process is illustrated in Fig. 2.8. The result is a flow that is much more three-dimensional than the one that preceded it. However, this is just one of several processes that may occur.

A single two-dimensional vortex is itself subject to instability. Imagine that the vortex develops a slight kink such as the one illustrated in Fig. 2.9. The self-induced velocity created by the kink will tend to lift it (whether it goes up or down depends on the geometry and the sign of the vorticity) and lengthen it in the streamwise direction. The final result will be a longitudinal or hairpin vortex.

If the vortex lies in a background shear flow, as is often the case, the lifting will also bring the tip of the kink into a region of (say) higher-speed flow that will pull the vortex and accentuate its stretching. This process is more effective

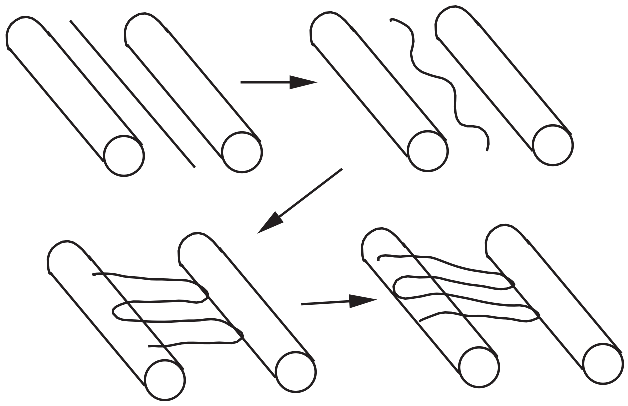

Fig. 2.8. The secondary (Lin–Corcos) instability process which produces longitudinal vortices.

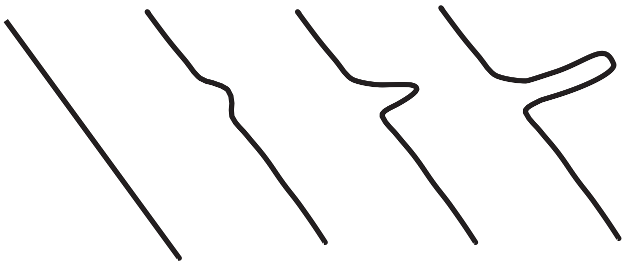

Fig. 2.9. A kink in a two dimensional vortex (left) develops into an extended longitudinal vortex (right).

at stretching the vortex and thus at distorting the flow than the one described above. If the vortex is a member of an array of similar vortices, such as the array resulting from Kelvin–Helmholtz instability, the stretching of the kink will induce kinking of the neighboring vortex, producing a kind of chain reaction. If this process is described by instability theory, the initial perturbation will be sinusoidal and a regular set of kinks will be produced, leading to a regular system of longitudinal vortices. (When this process occurs in vortex rings, it is known as the Widnall instability.) The longitudinal vortices, unlike the Kelvin–Helmholtz vortices, have alternating signs of the vorticity.

The kinking may also result in a process similar to pairing occurring locally. This has been called local pairing and, when it occurs in a regular manner over the length of the vortices, i.e. when it is described in terms of an instability, it is called helical pairing.

Local pairing can also result in a reconnection process in which the connected vortices separate again, but in a way that leaves a loop in the connected vortices.

Any of these processes produces a much more complex flow than the array of two-dimensional vortices that preceded it. Furthermore, the three-dimensional flow found at this stage is apparently much more sensitive to small disturbances than were the earlier stages of the flow and, in a relatively short time, the flow becomes a tangle of vortices; at this stage, most people would call the flow fully turbulent.

2.2.4 *Transition in wall-bounded flows*

In wall-bounded flows such as boundary-layer or channel flows, the process of transition from laminar to turbulent flow is quite different. In free shear flows, transition is caused by an instability that is essentially inviscid in nature; viscosity simply reduces its rate of growth. The instability requires that there be an inflection point (which is the same thing as a maximum in the vorticity) in the velocity profile. In wall-bounded flows the story is very different. To start with, the velocity profiles do not usually have inflection points (or, if they do, they occur at the wall) and are inviscidly unstable. Instability thus requires the presence of viscosity.

The analysis of the stability of wall-bounded flows is quite a bit more complicated than that for free shear flows. We merely cite a few key results. Because the laminar velocity profile does not contain an inflection point (there may be one at the wall that is not relevant), instability occurs only in the presence of viscosity and there is a minimum Reynolds number for instability; for the Blasius boundary layer, it is 5772, a rather high value. Beyond the critical Reynolds number the growth rates of the instability are generally much smaller than those caused by the inviscid instability of the mixing layer. Furthermore, below the critical Reynolds number, the decay of the least stable modes is very slow, so these modes may be regarded as a permanent part of the flow. Finally, experimental results show that transition usually occurs at Reynolds numbers far below the critical value, a result that was not explained until relatively recently.

The nature of the process was discovered through numerical simulation in the early 1980s. Although linear stability theory shows that the flow is stable with respect to two-dimensional perturbations, the least stable (slowest-decaying) modes for the boundary layer, which are called Tollmien–Schlichting waves, resemble the vortices produced by Kelvin–Helmholtz instability, i.e. they produce concentrations of vorticity. At sub-critical Reynolds numbers, the Tollmien–Schlichting waves are essentially a permanent part of the flow. These waves, if they are strong enough, may be subject to a secondary instability very similar to the ones found in free shear flows in which a kink is amplified and stretched to produce longitudinal vortices. Once these vortices have formed, transition to a fully developed turbulent state occurs very rapidly. The essential processes that complete the transition take place rather far from the wall.

Although the relatively orderly transition process just described can be produced in the laboratory and is very important for understanding some of what happens in a fully turbulent flow, naturally occurring flows often contain large perturbations (free-stream turbulence) that cause the transition process to occur in a much more haphazard way. We shall next describe this process.

2.2.5 *Bypass transition*

The picture of laminar–turbulent transition presented above is an orderly one in which an instability first produces an array of vortical structures. Then a secondary instability produces a more complex pattern of vortices. There may be tertiary instabilities but, finally, the flow becomes subject to so many simultaneous instabilities that it breaks down into the chaotic-looking flow that we call fully developed turbulence. This orderly progression to turbulence is a traditional picture that was accepted as *the* route to turbulence for a long time.

Although naturally occurring transition need not be so simple, the picture presented in the last paragraph gives a lot of insight into the mechanisms that operate in flows. Since many of the same mechanisms operate in turbulent flows, this picture has greatly increased our understanding of turbulence and, especially, of the coherent structures that are found in them. Indeed, research on the orderly transition process continues and is very important in its own right.

To produce the kind of transition we have just described in the laboratory, it is essential to assure that the flow entering the test section is extremely quiet, that is to say, the turbulence level must be very low. Investigations of this kind are important because they are relevant to transition on aircraft wings, the technology that initially drove research on transition. However, it has been recognized that there are other kinds of transition.

When the incoming flow contains a relatively high level of turbulence, that turbulence can induce a kind of transition, called *bypass* transition, that does not proceed through the orderly progression of states described earlier. Instead, there appears to be a rapid transition to a fully turbulent state without any apparent order or structure. The coherent structures that characterize turbulence may develop later. Although bypass transition is important, its very disorder makes it difficult to study in detail. As a result, it is not well understood and we shall say no more about it here.

2.3 Fully turbulent flows

When a flow is fully turbulent, i.e. when it has reached a state in which the averaged quantities change slowly with respect to downstream distance or time, it generally has a rough equilibrium between the rate at which turbulence is produced and the rate at which it is destroyed.

As we have noted, most flows of interest to geophysicists and engineers are dominated by shear. By this we mean that the largest changes in the velocity occur in directions that are approximately normal to the principal direction of the flow. In such flows, the principal mechanism for the production of turbulence and the transport of conserved quantities is similar to the one that we described earlier.

In this section, we shall look at some of the physical mechanisms that operate in turbulent flows. These will be seen to be quite similar to those involved in the transition process, so one might say that, in many flows, the flow remembers how it first became turbulent.

We shall begin with the simplest turbulent flows, two-dimensional turbulence, and homogeneous flows, and then discuss some turbulent shear flows.

2.3.1 Two-dimensional turbulence

If turbulence is constrained to be two-dimensional (in most laboratory situations this is nearly impossible), the only processes known to occur are the ones mentioned above: roll-up, pairing (or other agglomeration), and tearing. A two-dimensional flow can be regarded as a collection of discrete vortices. As noted, vortices of similar sign tend to combine to form larger vortices, whereas those of opposite signs tend to remain separate. As a result, after some time, a two-dimensional turbulent flow tends toward a state that consists of a relatively small number of large vortices. Thus the tendency in two-dimensional turbulence is for the energy to be transferred to ever larger scales.

There are other processes that play major roles in two-dimensional turbulence. For example, a two-dimensional finite vortex sheet (an example is found behind an aircraft wing) will tend to roll up like a carpet into something much more round (in the aircraft example, the sheets become the trailing vortices). Any vortex that is not circular will try to make itself more nearly circular since the circular vortex is the lowest-energy state.

On the other hand, the conservation law for angular momentum dictates that, when vortices combine or an irregularly shaped vortex becomes more circular, not all of the vorticity can enter the core of the resultant vortex. In fact, some part of the vorticity is found in thin filaments outside the large vortex; they resemble the arms of a spiral galaxy. The consequence of the creation of filaments is that, although fluctuations in the energy are transferred to large scales, fluctuations of vorticity (called enstrophy) are transferred to smaller scales.

Although the turbulence that geophysicists and engineers deal with is almost always three-dimensional, two-dimensional turbulence is very nearly realized in the atmosphere and the oceans. Because the vertical length scale in these flows is much smaller than the horizontal length scales, the magnitude of the vertical velocity is much smaller than the magnitude of the horizontal velocity components (especially on the largest scales), making the turbulence essentially two-dimensional on the largest length scales. The large vortices are seen as the big weather systems in satellite photos and as the mean circulation and large gyres found in the ocean.

Furthermore, even though turbulence in geophysical and engineering systems is three-dimensional, the two-dimensional processes of vortex agglomeration still play a significant role in them. Pairing may occur but, when it does, it occurs locally; only parts of each participating vortex merge. Tearing may also occur locally. These processes are responsible for much of the transfer of energy to large scales that is important in three-dimensional turbulence.

2.3.2 Homogeneous turbulence

Homogeneous turbulence is, by definition, a flow whose state is independent of location from a statistical point of view. This means that measurement of any averaged quantity yields identical results at any point in the flow. In the laboratory, an approximation to homogeneous turbulence is created by passing a flow through a screen, which produces uniform turbulence. Homogeneous turbulence may be subjected to various "extra strains," provided that they are independent of position in the flow; these include strain (plane, axisymmetric, or more general), shear, rotation, stratification, compression, and combinations of these.

Many of the processes observed in inhomogeneous turbulence are also found in homogeneous turbulence. What is probably most interesting is that, in geophysical and

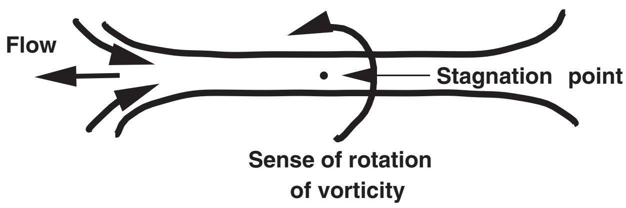

Fig. 2.10. A typical "worm" found in isotropic turbulence.

engineering flows, the most common type of "strain" is shear, whereas in the homogeneous flows, a much wider variety of mean strains is readily produced. This makes them interesting to study and difficult to model, principally because the dominant type of structure is different in each flow. The structures are generally vortices of the type that is most amplified by the imposed strain.

In isotropic turbulence, the simplest homogeneous flow, there is no strain of any kind. Therefore no energy is added to the turbulence (there is no "production") and the turbulence decays. It is possible to force the large scales and thereby maintain isotropic turbulence in a steady statistical state in simulations, but there is no way to do this in the laboratory.

Despite the simplicity of this flow, it does develop characteristic structures. Long thin vortices (called "worms") are created and seem to be responsible for much of the dissipation. They are illustrated in Fig. 2.10. It is not yet known whether these structures also exist in other turbulent flows. If they do, it may be important to consider them in turbulence modeling. An explanation of their creation and long lifetimes was given by Jiménez and Orlandi (1993).

Because shear flows are important to geophysicists and engineers, it is worthwhile to consider what happens in homogeneous shear flow; to be definite, we assume that the mean flow is in the x direction and its gradient is entirely with respect to the y direction, i.e. $\partial U/\partial y$ is the only non-zero derivative of the mean velocity. At moderate shear rates, the dominant type of structure is very similar to the ones found in free shear flows and wall-bounded flows. One finds "hairpins," vortices with heads transverse to the mean flow (in the z direction) and legs that are rather close together and inclined at about 45° with respect to the direction of the mean flow extending backward in the direction of the mean flow from the head. The vorticity in the two legs is of opposite sign and so the legs act as a pump that moves conserved quantities vertically through the flow. (For more details, see Moser and Rogers, 1993.)

At high shear rates, the vortices become almost parallel to the flow (x) direction as was demonstrated by Lee *et al.* (1993), who speculated that these structures might be related to the streaks found in the near-wall region.

2.3.3 *Fully developed shear flows*

When a free shear flow or a boundary layer reaches the stage at which the turbulence is said to be fully developed, it continues to grow in thickness but only very slowly. The mean turbulence quantities also change relatively slowly and one speaks of the flow being in "equilibrium," which means that there is a near balance between the rate at which turbulence energy is produced (more precisely, the rate at which energy is transferred from the mean flow to the turbulence) and the rate at which turbulence energy is dissipated (more precisely, transferred to internal energy of the fluid by the action of viscosity).

The above is based on the conventional view in which a turbulent flow is considered to be composed of a mean flow and fluctuations that constitute the turbulence. Implicit in this view is the notion that the fluctuations are small in some sense. It is also worth noting that, in other contexts in which concepts of this kind are used, the fluctuations are regarded as random. Historically, this decomposition, which originated with Osborne Reynolds, was applied to turbulence as well. As we have shown above, there is ample reason for believing that turbulence is not of this character. Nonetheless, this view persists and colors much of the thinking in turbulence research. We shall return to this subject later.

Provided that no additional significant forces or strains are imposed on the turbulence, the processes that produce turbulence in a fully developed flow are apparently quite similar to those in the transition process. We say apparently because the case is far from closed at this time, but it has been verified for low-Reynolds-number flows that have been studied in the laboratory and/or by simulation; it is yet not known whether it remains true at high Reynolds number. When the Reynolds number is high, the ratio of noise to coherent structures increases, making it difficult to find the latter, assuming that they do indeed exist.

Thus, in free-shear flows, stretching of vortices by the mean flow continues to be the major mechanism for the production of turbulence. In free-shear flows, vortex pairing on a local basis appears to be an important process, as is the production of hairpin vortices by the stretching produced by the mean shear. Pumping of fluid by the hairpins remains responsible for much of the transfer of conserved properties across the flow. A major difference is that the hairpins are not as clearly defined in fully developed turbulence. This will become clearer when we look at the boundary layer.

2.3.4 *Wall-bounded flows*

The differences, at least from the structural point of view, between wall-bounded shear flows and free shear flows is not as great as one might think. The effects of the wall are impermeability (prohibition of flow through the wall) and a no-slip condition (frictional reduction of the