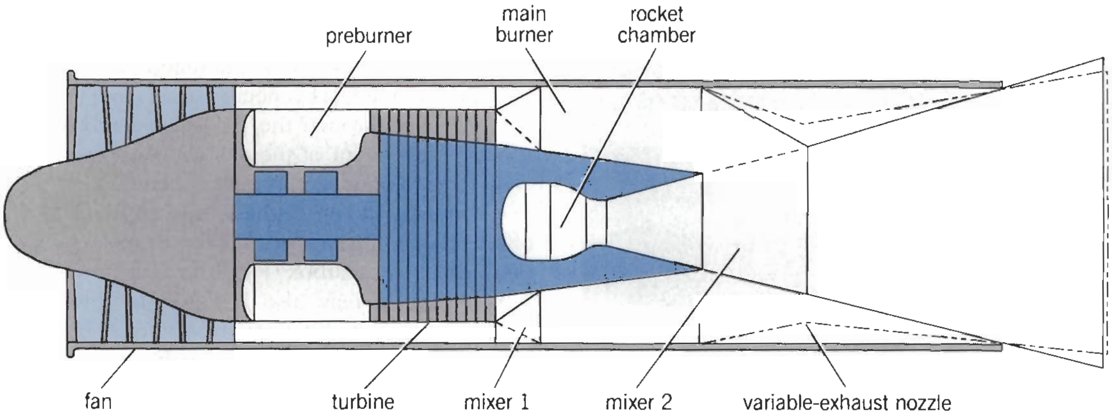


Section drawing of an air turboramjet with rocket combustion chamber for exoatmospheric flight. Such a power plant would combine turbojet, ramjet, and rocket propulsion modes. (*Aerojet*)

that may be harnessed in various ways for propulsion: through a jet nozzle, or through a supplementary turbine to drive a fan, propeller, or helicopter rotor. The compression process is generally supplemented during flight by the ram pressure rise that the air experiences as it is slowed down in the process of being drawn into the engine. In the case of very high supersonic flight, this ram pressure ratio is extremely large, of the order of 500:1 for flight Mach number 5. *See* BRAYTON CYCLE; TURBINE PROPULSION.

In the limiting case, the turbo-compressor is no longer necessary, and the engine design evolves into a ramjet, without any turbomachinery. Although the ramjet is an ideal engine for operation at these very high flight speeds, it is very inefficient at subsonic flight speeds and, indeed, it is useless for propulsion at the very low speeds appropriate to takeoff and landing. A turbofan has the opposite and complementary characteristics: very high efficiency at low flight speeds, and very low efficiency in very high supersonic flight. The turboramjet is configured to exploit the advantages of both engine types and to provide for efficient propulsion over the entire flight spectrum from takeoff to high supersonic cruise.

Engine configuration. For operation at subsonic and transonic flight speeds, fuel together with an appropriate amount of an oxidizer such as liquid oxygen is introduced into the preburner in the middle of the engine, where the mixture is burned (see **illus.**). The resultant hot high-pressure gas stream is expanded through a turbine that drives the fuel and oxidizer pumps and also powers a large fan in the front of the engine. The front-fan discharge air bypasses the preburner and tubine and enters the main burner through a mixer, where it joins the gas stream exiting from the turbine. The stream of mixed gases is then accelerated through a variable-area exhaust nozzle to provide the required propulsive thrust. Thrust augmentation may be obtained by injecting an excess of fuel in the preburner so that, when the fan air is mixed with the fuel-rich turbine exhaust, additional combustion, or afterburning, takes place in the main burner. *See* AFTERBURNER.

At very high flight speed, with air at very high ram pressure entering the engine, the pumping action of the fan is no longer necessary and the fan may be feathered, or otherwise made inoperative, while permitting the ram air to pass through. Propulsion is now provided exclusively by the combustion of the ram air in the main burner with the fuel-rich gas stream from the preburner.

For aircraft that are designed to proceed from high-speed atmospheric flight to transatmospheric flight, a rocket chamber may be provided in the engine where fuel and oxidant are burned in greater quantity than is possible in the preburner, and the exhaust stream may be discharged through the thrust nozzle without having to pass through the turbine.

Application. The turboramjet was invented in the late 1940s. A prototype of the basic engine system was proof-tested in the United States in the late 1950s. Very intensive study and some preliminary development is under way in the United States, Japan, Russia, and Europe, with the goal being a new generation of very high-speed transport aircraft that may use the turboramjet or a related engine type. *See* AIRCRAFT ENGINE; AIRCRAFT PROPULSION.

Fredric F. Ehrich

Bibliography. S. W. Korthals-Altes, Will the aerospace plane work, *Technol. Rev.*, pp. 43–51, January, 1987; B. Sweetman, Aerospace planes and trans-atmospheric vehicles, *Interavia*, pp. 305–308, March 1986.

Turbulent flow

A fluid motion in which velocity, pressure, and other flow quantities fluctuate irregularly in time and space. **Figure 1** shows a slice of a water jet emerging from a circular orifice into a tank of still water. A small amount of fluorescent dye mixed in the jet makes it visible when suitably illuminated by laser light, and tags the water entering the tank.

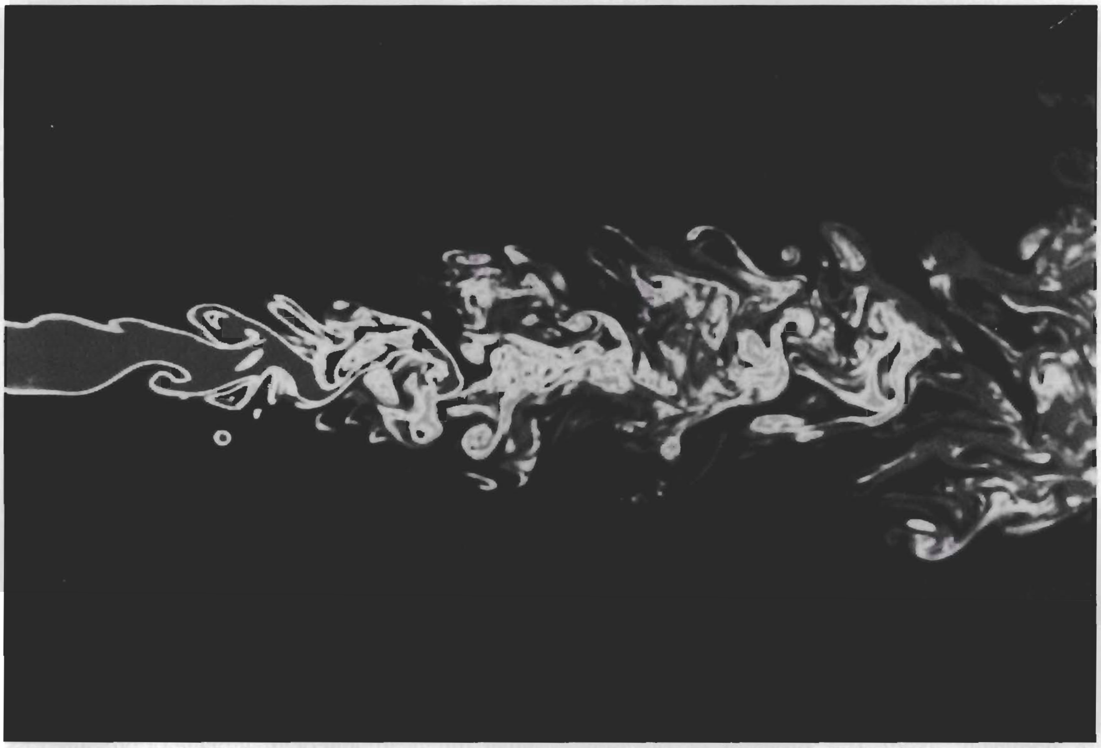


Fig. 1. Two-dimensional image of an axisymmetric water jet, obtained by the laser-induced fluorescence technique. A neodymium:yttrium-aluminum-garnet laser beam, shaped into a sheet of 250-micrometer thickness by using suitable lenses, was directed into a water tank into which the jet fluid, containing small amounts of uniformly dispersed fluorescing dye (sodium fluorescein), was emerging. The laser had a power density of 2×10^7 J/s per pulse and a pulse duration of about 10 nanoseconds. The flow is thus frozen to a good approximation. The region imaged extends from 2 diameters downstream of the orifice to about 18 diameters. The Reynolds number based on the orifice diameter, the velocity at the orifice, and the viscosity of water is about 2000. (*From R. R. Prasad and K. R. Sreenivasan, Measurement and interpretation of fractal dimension of the scalar interface in turbulent flows, Phys. Fluids A, 2:792–807, 1990*)

In this and similar realizations of the flow, there is a small region close to the orifice where the dye concentration does not vary with position, or with time at a given position. This represents a steady laminar state. Generally in laminar motion, all variations (if they occur at all) of flow quantities, such as dye concentration, fluid velocity, and pressure, are smooth and gradual in time and space. Farther downstream, the jet undergoes a transition to a new state in which the eddy patterns are complex, and flow quantities (including vorticity) fluctuate randomly in time and three-dimensional space. This is the turbulent state. *See* JET FLOW; LAMINAR FLOW.

Turbulence occurs nearly everywhere in nature [in the Earth's boundary layer (extending to more than a few hundred meters upward from the ground), the jet stream, cumulus clouds, rivers and oceans, the stellar atmosphere, interstellar gas clouds, and so forth] and in technology (in flow over airplanes, flow over turbine blades, flow of natural gas and oil in pipelines, combustion systems, and so forth). Two important characteristics of turbulence are the efficient dispersion and mixing of vorticity, heat, and contaminants. In flows over solid bodies such as airplane wings or turbine blades, or in confined flows through ducts and pipelines, turbulence is responsible for increased drag and heat transfer. Turbulence is therefore a subject of great engineering interest. On the other hand, as an example of collective interaction of many coupled degrees of freedom, it is also a subject at the forefront of classical physics. *See* DEGREE OF FREEDOM (MECHANICS); DIFFUSION; HEAT TRANSFER; PIPE FLOW; PIPELINE.

Figure 1 demonstrates the principal issues associated with turbulent flows. The first is the mechanism (or mechanisms) responsible for transition from the steady laminar state to the turbulent state even though, for both states, the governing equations (the Navier-Stokes equations) are the same, and the same smooth and symmetric boundary conditions are imposed on the flow everywhere. A second issue concerns the description of fully developed turbulence typified by the complex state far downstream of the orifice. To understand and describe the essential features of these spatial patterns, their interactions and temporal evolution, and to develop on this basis a rational theory capable of predicting flow features, is at the heart of turbulence theories. Finally, it is of technological importance to be able to alter the flow behavior to suit particular needs: Delaying transition to turbulence, or promoting it, or affecting the spread rate of the jet, or decreasing the drag of an airplane wing, or relaminarizing a turbulent flow some distance downstream of where it has become turbulent are some examples. Together, these three aspects—the origin of turbulence, the dynamics of fully developed turbulence, and the control of turbulent flows—constitute the turbulence problem. The problem assumes richer complexion when effects such as buoyancy, compressibility, electromagnetic conductivity, and chemical reactions are included. In spite of sustained efforts, turbulence has remained unsolved. Less is known about eddy motions on the scale of centimeters and millimeters than about atomic structure on the subnanometer scale, reflecting the complexity of the turbulence problem. *See* NAVIER-STOKES EQUATIONS.

Origin of turbulence. A central role in determining the state of fluid motion is played by the Reynolds number. In general, a given flow undergoes a succession of instabilities with increasing Reynolds number and, at some point, turbulence appears more or less abruptly. It has long been thought that the origin of turbulence can be understood by sequentially examining the instabilities. This sequence depends on the particular flow and, in many circumstances, is sensitive to a number of details even if the gross features in a given flow are nominally fixed. The program of precisely identifying the various instabilities culminating in fully developed turbulence has not been carried out for any flow, but a careful analysis of the perturbed equations of motion has resulted in a good understanding of the first two instabilities (primary and secondary) in a variety of circumstances. *See* REYNOLDS NUMBER.

Since the onset of turbulence resembles the onset of complexity in nonlinear systems in general, the universality theories describing the onset of chaos have been thought to bear on the transition to turbulence in fluid flows. The spirit of universality is that, no matter what equations govern a low-dimensional system, its behavior in the vicinity of bifurcations depends on certain generic features in phase space. This issue is an active area of research, and the experience so far has been that the onset of chaos in special types of flows under special circumstances follows these theories, at least to a very good approximation, but the relation between chaos (or temporal stochasticity) and fluid turbulence (which possesses temporal as well as spatial randomness, and large-scale order underlying the latter) remains unclear. *See* CHAOS.

Fully developed turbulence. Some of the principal difficulties in fully developed turbulence are the following: (1) The equations of motion are nonlinear, possess no general solutions, and permit few statements of general validity to be made; there is no small parameter in the problem on the basis of which approximate solutions can be deduced rationally. (2) There is no well-understood working model of turbulence that replicates its essential properties. (3) Turbulent velocity fluctuations at small scales are strongly nongaussian, this being an essential feature. (4) The number of degrees of freedom is very large. *See* DISTRIBUTION (PROBABILITY).

An estimate of the number of degrees of freedom is given by the quantity $(L/\eta)^3$, where L is the characteristic size of the large eddy in the flow (or an upper bound for the eddy scale either excited by inherent instability or forced by an outside agency), and η is the smallest scale below which all eddy motions are damped by viscosity. This number increases with the flow Reynolds number according to its 9/4 power. Three-quarters of the way downstream from the orifice in Fig. 1, the ratio L/η is of the order of 100. Although such flows can now be computed directly, the prospect at high Reynolds numbers remains discouraging—for the atmosphere, L is of the order of a few kilometers whereas η is of the order of a millimeter—even though computational capabilities have continued to increase rapidly and parallel processing has been much considered as a tool for expanding the scope of computation. *See* CONCURRENT PROCESSING; SUPERCOMPUTER.

Quite often in engineering, the detailed motion is not of interest, but only the long-time averages or means, such as the mean velocity in a boundary layer, the mean drag of an airplane or pressure loss in a pipeline, or the mean spread rate of a jet. It is therefore desirable to rewrite the Navier-Stokes equations for the mean motion. The basis for doing this is the Reynolds decomposition, which splits the overall motion into the time mean and fluctuations about the mean. These macroscopic fluctuations transport mass, momentum, and matter (in fact, by orders of magnitude more efficiently than molecular motion), and their overall effect is thus perceived to be in the form of additional transport or stress. This physical effect manifests itself as an additional stress (called the Reynolds stress) when the Navier-Stokes equations are rewritten for the mean motion (the Reynolds equations). The problem then is one of prescribing the Reynolds stress, which contains the unknown fluctuations in quadratic form. A property of turbulence is that the Reynolds stress terms are comparable to the other terms in the Reynolds equation, even when fluctuations are a small part of the overall motion. An equation for the Reynolds stress itself can be obtained by suitably manipulating the Navier-Stokes equations, but this contains third-order terms involving fluctuations, and an equation for third-order terms involves fourth-order quantities, and so forth. Thus, at any stage of the process, which can be continued indefinitely, there are more unknowns than equations; that is, the system of equations is not closed. This is the closure problem in turbulence. The Navier-Stokes equations are themselves closed, but the presence of nonlinearity and the process of averaging result in nonclosure.

Given this situation, much of the progress in the field has been due to (1) exploratory experiments and numerical simulations of the Navier-Stokes equations at low Reynolds numbers;

and (2) plausible hypotheses in conjunction with dimensional reasoning, scaling arguments, and their experimental verification.

Experiments, for long the central tool of research in turbulence, are limited to measuring a small number of parameters at a few positions in high-Reynolds-number flows. Low-Reynolds-number flows (at least some of their features) can be quantitatively mapped in three dimensions by using lasers and advanced optical techniques; this Reynolds number range is also the one for which numerical simulations are currently possible. From a combination of such studies, it has been learned, among other things, that the magnitude of the dissipation rate of turbulent kinetic energy is independent of viscosity (even though viscosity is essential for dissipation); that the boundary between the turbulent and nonturbulent regions in high-Reynolds-number free shear flows such as jets is sharp and fractallike; that the dissipation of energy is highly intermittent in space; that some events that appear to be dynamically significant are also intermittent and perhaps quasicyclic; and that, when the flow scales are suitably coarse-grained, some degree of spatial order on scales of order L is visible even at very high Reynolds numbers, especially if the flow development in time is observed. The true significance of each of these features in accomplishing transport is still under active research. *See* FRACTALS; VISCOSITY.

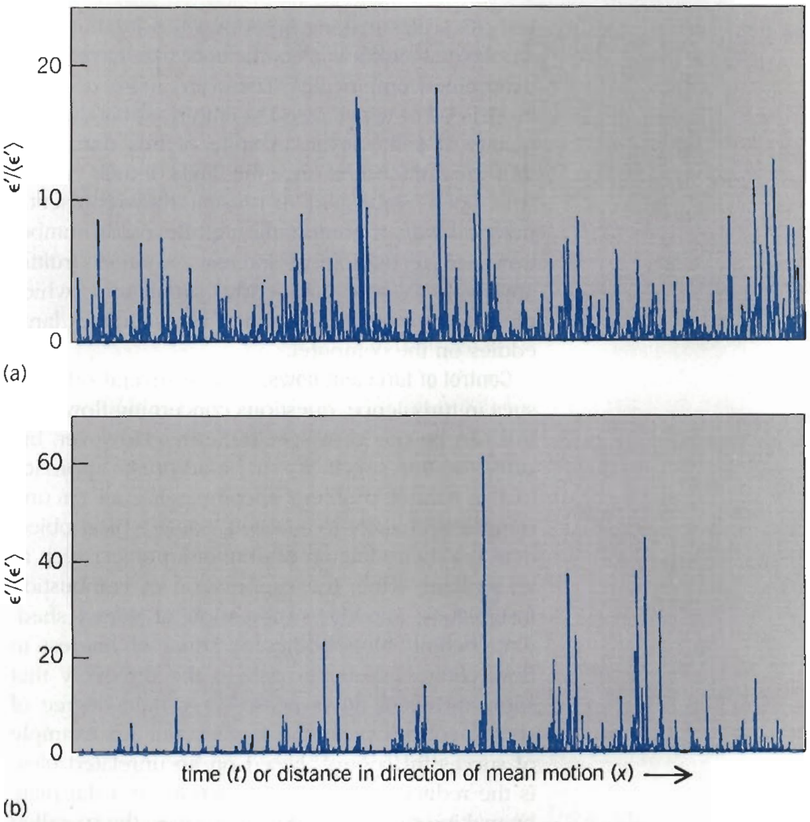


Fig. 2. Typical signals of ϵ', a component of the turbulent energy dissipation, normalized by its mean value $\langle\epsilon'\rangle$. (*a*) Signal obtained in a laboratory turbulent boundary layer at a moderate Reynolds number (defined suitably). (*b*) Signal obtained in the atmospheric surface layer at a high Reynolds number. (*After C. Meneveau and K. R. Sreenivasan, Simple multifractal cascade model for fully developed turbulence, Phys. Rev. Lett., 59:1424–1427, 1987*)

The intermittency in space of the turbulent energy dissipation is shown at moderate (**Fig. 2*a***) and high (Fig. 2*b*) Reynolds numbers. The signal becomes less space-filling or more intermittent as the Reynolds number increases. In particular, the big spikes in Fig. 2*b* are many times larger than the corresponding ones in Fig. 2*a*. This intermittency, representing the fact that there is a limit to the mixing at small scales, is believed to be an important feature of turbulence. It is not entirely clear how this feature arises dynamically, but it can be modeled well by a simple multiplicative process.

A classic and celebrated hypothesis is the concept of local isotropy, which assumes that small scales of motion are isotropic irrespective of the gross orientation of the mean flow, and thus possess some universality. A second notion is the matchability between behaviors of highly disparate scale ranges so that a functional form for average quantities of interest can be determined for the intermediate scale range. For example, in the turbulent boundary layer over a flat wall, this type of argument leads to a logarithmic variation of mean velocity with height for heights large compared to the viscous scale and small compared to the overall thickness of the boundary layer. Similarly, intermediate scales that are large compared to η but small compared to L (the so-called inertial range) are expected to possess self-similarity, leading to power-law variations for the spectral densities of energy, dissipation, variance of concentration fluctuations, and so forth. These predictions have received experimental support, and, in fact, they seem to be realized under conditions where they are not necessarily expected to be valid, based on first principles. This raises the possibility that the basic theoretical arguments of this type (which, incidentally, do not make much use of the Navier-Stokes equations) have a much wider range of validity. It should be emphasized that these arguments predict an absolute number in the inertial range, but not elsewhere. *See* BOUNDARY-LAYER FLOW.

Certain specific questions of engineering interest can be answered quickly by modeling the Reynolds stress in a variety of ways and closing the Reynolds equations. The earliest model, based on analogies with molecular motion, postulated that the physical motion of eddies over well-defined distances accomplishes transport. The resulting eddy viscosity—essentially the product of a characteristic velocity scale and a length scale of turbulent motion—is the analog of molecular viscosity. Even though there are circumstances where the eddy-viscosity approach works roughly, the concept has many drawbacks and is not very useful as a general idea; in any case, the eddy viscosity varies from flow to flow and from point to point in a given flow. In the next level of models, separate equations are written for the length and velocity scales making up eddy viscosity, but there are several unknown coefficients that have to be determined empirically. There are more complex models, all of which resort to empiricism of dubious quality at some level. In spite of this drawback, they are quite useful once the limits of their validity have been established. At present, they represent a practical way of computing high-Reynolds-number flows of technological interest. Another fruitful approach is the large-eddy simulation, which models the small-scale motion but simulates large eddies on the computer.

Control of turbulent flows. Unlike several other issues in turbulence, questions concerning flow control can be posed in specific terms. However, because of this specificity, a broad-brush approach to the control problem encompassing all circumstances is unlikely to succeed. Some typical objectives are the reduction of drag of an object such as an airplane wing, the suppression of combustion instabilities, and the suppression of vortex shedding behind bluff bodies. A surge of interest in flow control is due in part to the discovery that some turbulent flows possess a certain degree of spatial coherence at the large scale. An example of successful control, based on an unrelated idea, is the reduction of the skin friction on a flat plate by making small longitudinal grooves, the so-called riblets, on the plate surface, imitating shark skin.

Prospects. Progress in the turbulence problem depends on the capability to make accurate measurements in high-Reynolds-number flows, the increase in computer power, the invention of new tools for handling large streams of stochastic data, and a judicious combination of all of them. Unfortunately, simply computing or making measurements in a highly nonlinear system such as turbulent flow does not always add to understanding. Although several new analytical tools, graphical display capabilities, and data-compression and data-handling techniques are being explored, it is difficult to predict what true progress is likely to occur through the 1990s. It is clear, however, that turbulence will spur important activity in a number of disciplines at the forefront of science and technology; conversely, it will benefit from them. In the long run, perhaps, all these tools can enhance the qualitative understanding of turbulence; to obtain quantitative data in a specific context, reliance may always have to be placed on experiment, as well as modeling and computation that use this qualitative knowledge in a sensible way. This would resemble to some extent the situation in quantum chemistry. *See* FLUID FLOW; FLUID-FLOW PRINCIPLES. **K. R. Sreenivasan**

Bibliography. H. Bai-Lin (ed.), *Chaos II*, 1990; D. M. Bushnell and C. B. McGinley, Turbulence control in wall flows, *Annu. Rev. Fluid Mech.*, 21:1–20, 1989; R. J. Garde, *Turbulent Flow*, 1994; J. L. Lumley, *Whither Turbulence? Or, Turbulence at Crossroads*, 1990; H. L. Swinney and J. P. Gollub (eds.), *Hydrodynamic Instabilities and the Transition to Turbulence*, 2d ed., 1985; H. Tennekes and J. L. Lumley, *A First Course in Turbulence*, 1972; A. A. Townsend, *The Structure of Turbulent Shear Flows*, 2d ed., 1976.

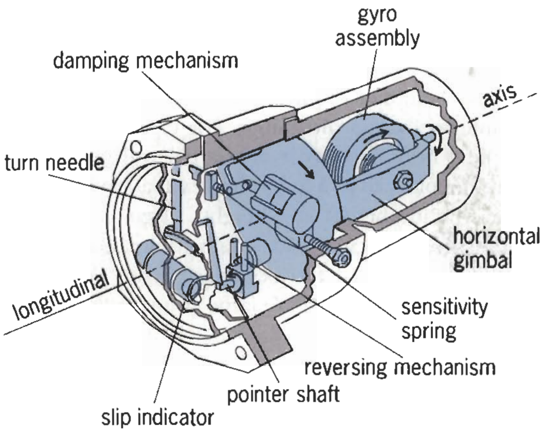
Turmeric

A dye or a spice obtained from the plant *Curcuma longa*, which belongs to the ginger family (Zingiberaceae). It is a stout perennial with short stem, tufted leaves, and short, thick rhizomes which contain the colorful condiment. As a natural dye, turmeric is orange-red or reddish brown, but it changes color in the presence of acids or bases. As a spice, turmeric has a decidedly musky odor and a pungent, bitter taste. It is an important item in curry and is used to flavor and color butter, cheese, pickles, and other food. *See* SPICE AND FLAVORING; ZINGIBERALES. **Perry D. Strausbaugh/ Earl L. Core**

Turn and bank indicator

A combination instrument which provides an aircraft pilot with two distinct pieces of information: the aircraft's rate of turn about the vertical axis, and the relationship between this rate and the aircraft's angle of bank. It is also known as the needle and ball indicator or the turn and slip indicator.

The turn needle is operated by a gyroscope and indicates the rate at which the aircraft is turning about the vertical axis in degrees per second. Semirigid mounting of the gyro permits it to rotate freely about the lateral and longitudinal axes while restricting motion about the vertical axis (see **illus.**). In a turn, gyroscopic precession causes the rotor to tilt in the direction opposite the turn with a magnitude proportional to the turn rate. A mechanical linkage converts this precession to reversed movement of a turn needle, thus indicating proper turn direction. A spring attached between the gyro assembly and the instrument case holds the gyro upright when precession force is not



Typical turn and bank indicator. (*U.S. Air Force*)