reflecting deficiencies in the tuberculin skin test, in terms of the specificity (failure to correctly identify uninfected animals) and the sensitivity (failure to correctly identify infected animals).

The natural history of this Texas area highlights the difficulty of ridding infected herds of tuberculosis by tuberculin skin-testing procedures alone. The long-term history of the program has shown that about one-third of all herds not depopulated can be expected to remain infected when released from quarantine. The advent of large dairy herds that have not been depopulated has increased the overall recurrence rate of tuberculosis in herds to about 50%. Until tests are developed that improve the detection rate of infected individual animals, it is not likely that the success rate will be improved.

Government regulations. State and federal animal health regulations require that a thorough epidemiological investigation be conducted in all cases of bovine tuberculosis to determine the source of introduction of disease, and to identify and trace all potentially exposed contact animals and herds. Investigations resulting from recent cases include mandatory tests of all herds identified as potential sources, test or slaughter of all exposed animals which have previously been sold from affected herds, testing of adjacent cattle herds, and areawide tests of all dairies.

Molecular epidemiology. Molecular epidemiology using restriction-fragment-length polymorphisms to type each of the isolates is providing a new approach to tracking the transmission of the organism. The dramatic differences in observed reactor rates and lesion rates between herds may be accounted for by differences in herd susceptibility, considering management factors, age structure, nutrition, herd genetics, and culling rates, and the duration of disease in the herd. However, empirical evidence suggests that consideration of these rates, along with noted differences in pathological observations, may indicate differences in the virulence of the organism as well. If strain differences of *M. bovis* do occur, identification of specific types by restriction-fragment-length polymorphism typing would likely provide information relating to source of exposure, prognosis for the herd, risks associated with decisions to elect test-and-slaughter rather than depopulation, and risks associated with traced-exposed animals lost in trade channels. Additional risk factors which have been identified but not adequately investigated include the practice of back-grounding, that is, conditioning dairy heifers in plots of land on which livestock are fattened for market (feedlots); geographical proximity of the heavily infected milksheds; and the potential of human, wild, and feral animals as vectors or reservoirs of *M. bovis*.

Because livestock populations that are free of tuberculosis are essential in order to maintain food safety, public health, and safe intrastate, interstate, and international trade, control leading to the eradication of the disease from livestock remains the paramount goal for most nations. This goal remains attainable, but its timely achievement will require increased commitment from its major stakeholders: the affected industries, state and federal animal health agencies, veterinarians, educators, and research scientists.

Control. Educating, training, and informing the public are very important aspects of developing an effective disease control program. In the past, the progress of the tuberculosis eradication program has reduced the prevalence of the disease, and has placed most associated people at least two generations removed from acquiring an understanding of the disease and gaining experience with its impact in both humans and animals. Currently, it is unlikely that beef or dairy producers have seen clinical cases of the disease in cattle or know people who have contracted the disease. The same applies to the associated industries: most veterinarians have not had direct experience with the disease, and slaughterhouse workers and inspectors are unfamiliar with actual cases.

The primary method for detecting infection in traditional national control programs has involved tuberculin skin testing of all cattle herds within defined geographic areas with slaughter of all positive animals, but this approach often is not feasible because of the high cost of replacement animals. Previously identified issues in the current eradication program which require consideration include improved methods and delivery of disease surveillance, indemnity for destruction of infected and exposed animals, regulatory modifications to minimize risks associated with infected imported animals, and educational efforts to improve awareness and appreciation of bovine tuberculosis as an integral part of routine herd health problems.

For background information *see* BEEF CATTLE PRODUCTION; EPIDEMIOLOGY; PUBLIC HEALTH; TUBERCULOSIS in the McGraw-Hill Encyclopedia of Science & Technology. L. Garry Adams

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Turbulent flow

Recent advances in the study of turbulent flow include the development of techniques of active control for suppressing turbulence, and the development of the technique of large-eddy simulation for the prediction of complex turbulent flows.

Control of Turbulence

Preventing the transition of a laminar flow to turbulence and suppressing the fluctuations of a turbulent flow, perhaps with the ultimate goal of returning the turbulent flow to a laminar state, are problems of great theoretical as well as practical importance. From the viewpoint of practical engineering, suppression of turbulence through appropriate control actions would provide a dramatic reduction of viscous drag and consequently of transportation costs. From the theoretical viewpoint, control of turbulence is a test of the completeness of physical theory, and understanding the physical mechanism of turbulence should lead either to methods of control or to an explanation of why control fails in some cases.

The turbulence control problem is made more difficult by the fact that theory does not specify the magnitude and structure of the perturbations that necessarily lead to a transition between the laminar and turbulent states. However, there is ample experimental evidence that sufficiently small perturbations fail to induce a transition, at least for Reynolds numbers less than 10^5, in simple pressure-driven shear flows in pipes. (The Reynolds number, *Re*, is a single dimensionless number characterizing the flow. It measures the ratio of the typical force required to produce observed accelerations in the fluid flow to the viscous force, and is defined for a fluid with characteristic velocity U, length scale L, density ρ, and viscosity μ by $Re = \rho UL/\mu$.) This observation suggests that a control strategy that adequately suppresses the fluctuations may succeed in maintaining the laminar flow in some flow geometries.

Perturbation suppression. Perturbation energy in turbulent flows is concentrated in erratically recurring structures called coherent structures. Very near the bounding surface, these coherent structures are counterrotating streamwise vortices accompanied by regions of high and low velocity elongated in the direction of the flow, referred to as streamwise streaks. Farther from the boundary the streaks give way to vortices distorted into the form of horseshoes. Current attempts at active and passive control of turbulence aim to suppress or to cancel these developing coherent structures.

Because the exact degree of perturbation suppression necessary to maintain laminar flow is not known theoretically, turbulence control strategies can be verified only by experiment or by direct numerical simulation of the turbulence (which currently provides accurate turbulence simulations only at moderate Reynolds numbers of the order of 10^3, while turbulent-flow Reynolds numbers may be of the order of 10^6). A physical theory accounting for the emergence of coherent structures in the turbulent fluid is particularly valuable because it may lead to new control strategies.

Active versus passive control. Flow manipulation can proceed by passive or active means. In passive control the flow is modified by actions which do not require unsteady external input. Probably the most effective currently available means for passive suppression of turbulent fluctuations is introduction of polymers into the flow, which can lead to reduction of viscous drag by as much as 80%. Surface modifications, with grooves (riblets), large-eddy breakup devices, or convex bounding surfaces, have been shown to lead to passive reductions of viscous drag as large as 20%. The use of flexible boundaries, which deform in response to the overlying flow, has at times been claimed to lead to drag reduction, but the reductions have not been verified.

In active control, there is a dynamic input to the flow which either can be determined in advance (in open-loop control) or can be the coordinated reaction to real-time measurements of the actual flow state (in closed-loop or feedback control). An example of open-loop control is oscillation of the bounding surface in the spanwise direction (across the flow), which has been recently shown to lead to drag reduction of as much as 40%.

In feedback control the dynamic adjustment is accomplished by a combination of an observation produced by a device that detects some aspect of the flow state and a subsequent response produced by a mechanical activator. For example, real-time observation of the normal velocity near the wall followed by opposing wall transpiration (by applying blowing or suction) recently has been shown to lead to drag reductions of the order of 20%.

It is expected that with recent advances in technology, in particular the design of microelectronic devices that can measure fluid properties and be programmed to provide feedback in a designed manner, it will be possible to implement a wide variety of active control strategies in the near future. *See* MICROSENSOR.

Optimal active control. It has been proposed recently that the present capabilities of numerical simulation of turbulence suffice for the identification of the optimal active control. Optimal control is the flow manipulation that minimizes a cost functional. In turbulence research, this functional is often taken to be the drag. The well-developed optimal control theory commonly applied in the past to low-dimensional dynamical systems provides the technical underpinnings of this strategy. The optimal control is approached iteratively by estimating the sensitivity of the cost functional to various active control strategies. This sensitivity can be found by integrating the fluid equations forward, after which adjoint analysis is used to identify the directions of greatest sensitivity which identify the direction of optimal flow manipulation. This technique has reduced drag in computer simulations by an order of 20% using wall transpiration (blowing or suction) in antiphase with the observed vertical velocity of the flow above the boundary.

Theory of transition to turbulence. A widely accepted theory of transition to turbulence envisions unstable two-dimensional wave structures called Tollmien-Schlichting waves growing exponentially until they fall victim to secondary three-dimensional instabilities. These instabilities, in turn, give way to a cascade of further instabilities, and the ensemble of these exponential instabilities supports the turbulent state. Control strategies proceeding from this paradigm include passive means to lower the growth rate of the primary unstable Tollmien-Schlichting wave by using suction to change the velocity profile and by altering the viscosity of the flow through heating or cooling the surface. While attempts to depress growth rates using compliant boundaries have met little success, direct active cancellation of the Tollmien-Schlichting waves by introduction of antiphase perturbations has produced a delay in transition in carefully controlled experiments.

However, observations demonstrated that during transition the energetic nonmodal (perturbations which are not a single mode of the system) three-dimensional disturbances dominate the perturbation variance. This led researchers to propose a bypass theory of transition to turbulence according to which transition can occur through transient perturbation growth without the intercession of exponentially unstable Tollmien-Schlichting waves. Moreover, recent advances in a generalization of stability theory have identified the disturbances (called optimal perturbations) most likely to cause transition by growing the most over the time span during which transition occurs. These optimal initial perturbations were shown to evolve into the coherent structures which are typically observed during the transition to turbulence. Active control strategies following from this paradigm attempt to cancel or reduce the growth of these optimal initial perturbations rather than the growth of unstable Tollmien-Schlichting waves.

Control of existing turbulence. Turning from prevention of transition from the laminar to the turbulent state to suppression of already existing turbulence, the recent theoretical description of the coherent structures in the turbulent state enables the researcher to identify actions that can impede the growth of these structures. This development suggests that it may be possible to actively suppress turbulence by boundary forcing appropriately configured so as to cancel the emerging coherent structures which maintain the turbulent flow.

Petros J. Ioannou

Large-Eddy Simulation

Accurate prediction of the turbulent flows encountered in engineering practice remains the principal challenge of computational fluid dynamics. One primary difficulty with simulation and modeling is that turbulence comprises a wide range of length and time scales. The largest scales of motion are responsible for most of the momentum and energy transport and are strongly dependent on the flow configuration, while the smallest eddy motions tend to depend only on viscosity and are more universal (that is, similar, even in different flows) than the large eddies.

Large-eddy simulation is rapidly emerging as a viable technique for prediction of complex turbulent flows. In large-eddy simulation the contribution of the large, energy-containing scales of motion is computed directly, and only the effect of the smallest scales of turbulence is modeled. Since the small scales are more homogeneous and less affected by boundary conditions than the large eddies, it is possible to model them by using simpler models than those required in other techniques.

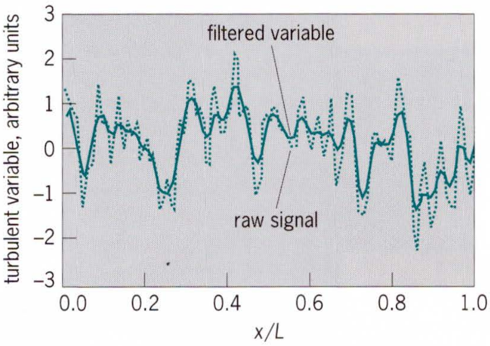

Fig. 1. Filtered variable computed in large-eddy simulation by spatially filtering the raw signal (such as density, velocities, or pressure). Here, *x* represents position, and *L* is the length scale of the system under study.

Motivation. Large-eddy simulation was originally developed because a direct solution of the equations describing the transport of mass, momentum, and energy—the Navier-Stokes equations—is beyond the capacity of even the largest supercomputers for flows of engineering interest. It is possible to characterize the computational cost of a direct simulation in terms of the Reynolds number, *Re*, which is the ratio of inertial to viscous forces and characterizes the state of fluid motion. Since the ratio of the largest to smallest turbulence length scale is proportional to $Re^{3/4}$, the number of grid points for a three-dimensional computation is proportional to $Re^{9/4}$. Because the number of time steps scales like $Re^{4/3}$, the cost of directly simulating the Navier-Stokes equations is at least proportional to Re^{3}. Even with the continued development of supercomputers, the rapid increase in cost with increases in Reynolds number limits application of direct numerical simulation to simple flows at low Reynolds number.

Filtering. In large-eddy simulation, transport equations are derived for the large eddies by spatially filtering the Navier-Stokes equations. Application of a filter to a representative turbulent variable is shown in **Fig. 1**. Variations of the fluctuating variable occurring on longer wavelengths (that is, larger scales) are preserved, while the shorter wavelength variation is removed by the filter. The mean value of the raw signal is retained following the filtering operation, but other statistics, such as cross correlations, will differ between the filtered and raw signals because of the absence of the small-scale contribution to the filtered signal. However, in turbulent flows many correlations of interest for engineering prediction are mostly influenced by the large scales of