Overview of Turbulence Control Research in U.S.A.

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ABSTRACT

This brief article reviews the important advances in the field of turbulent flow control that took place during the past few years. This broad area of research remains of great interest for its numerous potential benefits for both the military and civilian sectors. Spurred by the recent developments in chaos control, microfabrication and neural networks, reactive control of turbulent flows is now in the realm of the possible for future practical devices.

1. INTRODUCTION

The ability to manipulate a flow field to effect a desired change is of immense practical importance. As a scientific discipline and as a technological curiosity, flow control is perhaps more hotly pursued by scientists and engineers than any other area in fluid mechanics. Flow control involves passive or active devices to effect a beneficial change in wall-bounded or free-shear flows. Whether the task is to delay/advance transition, to suppress/enhance turbulence or to prevent/provoke separation, useful end results include drag reduction, lift enhancement, mixing augmentation and flow-induced noise suppression.

Considering the extreme complexity of the turbulence problem in general and the unattainability of first-principles analytical solutions in particular, it is not surprising that controlling a turbulent flow remains a challenging task, mired in empiricism and unfulfilled promises and aspirations. Brute force suppression, or *taming*, of turbulence via active, energy-consuming control strategies is always possible, but the penalty for doing so often exceeds any potential savings. The artifice is to achieve a desired effect with minimum energy expenditure

The present article reviews the important developments in the field of turbulent flow control that took place during the past seven years and suggests avenues for future research. The emphasis will be on reactive flow control for future vehicles and other industrial devices, but more market-ready methods of control will be briefly mentioned.

2. UNIFYING PRINCIPLES

For the purposes of the present section, we focus on the technologically very important boundary layers. An external wall-bounded flow, such as that developing on the exterior surface of an aircraft or a submarine, can be manipulated to achieve transition delay, separation postponement, lift increase, skin-friction and pressure drag reduction, turbulence augmentation, heat transfer enhancement, or noise suppression. These objectives are not necessarily mutually exclusive. For example, by maintaining as much of a boundary layer in the laminar state as possible, the skin-friction drag and the flow-induced noise are reduced. However, a turbulent boundary layer is in general more resistant to separation than a laminar one. By preventing separation, lift is enhanced and form drag is reduced. Moreover, mixing and heat transfer are enhanced by the turbulence. The challenge in choosing a flow control scheme is of course to achieve a beneficial goal at a minimum cost, without adversely affecting another goal. An ideal method of control that is simple, is inexpensive to build and to operate, and does not have any tradeoff does not exist, and the skilled engineer has to make continuous compromises to achieve a particular design objective.

There are different classification schemes for flow control methods. One is to consider whether the technique is applied at the wall or away from it. Surface parameters that can influence the flow include roughness, shape, curvature, rigid-wall motion, compliance, temperature, and porosity. Heating and cooling of the surface can influence the flow via the resulting viscosity and density gradients. Mass transfer can take place through a porous wall or a wall with slots. Suction and injection of primary fluid can have significant effects on the flow field, influencing particularly the shape of the velocity profile near the wall and thus the boundary layer susceptibility to transition and separation. Different additives, such as polymers, surfactants, micro-bubbles, droplets, particles, dust or fibers, can also be injected through the surface in water or air wall-bounded flows. Control devices located away from the surface can also be beneficial. Large-eddy breakup devices (also called outer-layer devices, or OLDs), acoustic waves bombarding a shear layer from outside, additives introduced in the middle of a shear layer, manipulation of freestream turbulence levels and spectra, gust, and magneto- and electro-hydrodynamic body forces are examples of flow control strategies applied away from the wall.

A second scheme for classifying flow control methods considers energy expenditure and the control loop involved. As shown in the schematic in Figure 1, a control device can be passive, requiring no auxiliary power, or active, requiring energy expenditure. As for the action of passive devices, some prefer to use the term flow management rather than flow control (Fiedler and Fernholz, 1990), reserving the latter terminology for dynamic processes. Active control is further divided into predetermined or reactive. Predetermined control includes the application of steady or unsteady energy input without regard to the particular state of the flow. The control loop in this case is open as shown in Figure 2a, and no sensors are required. Reactive control is a special class of active control where the control input is continuously adjusted based on measurements of some kind. The control loop in this case can either be an open, feedforward one (Figure 2b) or a closed, feedback loop (Figure 2c). Classical control theory deals, for the most part, with reactive control.

The distinction between feedforward and feedback is particularly important when dealing with the control of flow structures which convect over stationary sensors and actuators. In feedforward control, the measured variable and the controlled variable differ. For example, the pressure or velocity can be sensed at an upstream location, and the resulting signal is used together with an appropriate control law to trigger an actuator which in turn influences the velocity at a downstream position. Feedback control, on the other hand, necessitates that the controlled variable be measured, fed back and compared with a reference input. Reactive feedback control is further classified into four categories: adaptive, physical model-based, dynamical systems-based, and optimal control (Moin and Bewley, 1994).

A yet another classification scheme is to consider whether the control technique directly modifies the shape of the instantaneous/mean velocity profile or selectively influence the small dissipative eddies. An inspection of the Navier-Stokes equations written at the surface (see, for example, Gad-el-Hak, 1990), indicates that the spanwise and streamwise (streamwise vorticity exists only if the velocity field is three-dimensional, instantaneously or in the mean.) vorticity fluxes at the wall can be changed, either instantaneously or in the mean, via wall motion/compliance, curvature, suction/injection, streamwise or spanwise pressure-gradient (respectively), or normal viscosity-gradient. These vorticity fluxes determine the fullness of the corresponding velocity profiles. For example, suction, favorable pressure-gradient or lower wall-viscosity results in vorticity flux away from the wall, making the surface a source of spanwise and streamwise vorticity. The corresponding fuller velocity profiles have negative curvature at the wall and are more resistant to transition and to separation but are associated with higher skin-friction drag. Conversely, an inflectional velocity profile can be produced by injection, adverse pressure-gradient or higher wall-viscosity. Such profile is more susceptible to transition and to separation and is associated with lower, even negative, skin friction. Note that many techniques are available to effect a wall viscosity-gradient; for example surface heating/cooling, film boiling, cavitation, sublimation, chemical reaction, wall injection of lower/higher viscosity fluid, and the presence of shear thinning/thickening additive.

Flow control devices can alternatively target certain scales of motion rather than globally changing the velocity profile. Polymers, riblets and LEBUs, for example, appear to selectively damp only the small dissipative eddies in turbulent wall-bounded flows. These eddies are responsible for the (instantaneous) inflectional profile and the secondary instability in the buffer zone, and their suppression leads to increased scales, a delay in the reduction of the velocity-profile slope, and consequent thickening of the wall region. In the buffer zone, the scales of the dissipative and energy containing eddies are roughly the same and, hence, the energy containing eddies will also be suppressed resulting in reduced Reynolds stress production, momentum transport and skin friction.

3. REACTIVE CONTROL

3.1 Targeted Control

Numerous methods of flow control have already been successfully implemented in practical engineering devices. Yet, limitations exist for some familiar control techniques when applied to specific situations. For example, in attempting to reduce the drag or enhance the lift of a body having a turbulent boundary layer using global suction, the *penalty* associated with the control device often exceeds the *saving* derived from its use. What is needed is a way to reduce this penalty to achieve a more efficient control. Reactive control geared specifically towards manipulating the coherent structures in transitional and turbulent shear flows, though considerably more complicated than passive control or even predetermined active control, has the potential to do just that. As will be argued in this and the following three sections, future systems for control of transitional and turbulent flows in general and turbulent boundary layers in particular could greatly benefit from the merging of the science of chaos control and the technologies of microfabrication and neural networks. Such systems are envisaged as consisting of a large number of intelligent, communicative wall sensors and actuators arranged in a checkerboard pattern and targeted towards controlling certain quasi-periodic, dynamically significant coherent structures present in the wall region.

Successful techniques to reduce the skin friction in a turbulent flow, such as polymers, particles or riblets, seem to act indirectly through local interaction with discrete turbulent structures, particularly small-scale eddies, within the flow. Common characteristics of all these methods are increased losses in the near-wall region, thickening of the buffer layer, and lowered production of Reynolds shear stress (Bandyopadhyay, 1986). Methods that act directly on the mean flow, such as suction or lowering of near-wall viscosity, also lead to inhibition of Reynolds stress. However, skin friction is increased when any of these velocity-profile modifiers is applied globally.

Could these seemingly inefficient techniques, *e.g.* global suction, be used more sparingly and be optimized to reduce their associated penalty? It appears that the more successful drag-reduction methods, *e.g.* polymers, act selectively on particular scales of motion and are thought to be associated with stabilization of the secondary instabilities. It is also clear that energy is wasted when suction or heating/cooling is used to suppress the turbulence throughout the boundary layer when the main interest is to affect a near-wall phenomenon. One ponders, what would become of wall turbulence if specific coherent structures are to be targeted, by the operator through a reactive control scheme, for modification? The myriad of organized structures present in all shear flows are instantaneously identifiable, quasi-periodic motions (Cantwell, 1981; Robinson, 1991). Bursting events in wall-bounded flows, for example, are both intermittent and random in space as well as time. The random aspects of these events reduce the effectiveness of a predetermined active control strategy. If such structures are nonintrusively detected and altered, on the other hand, net performance gain might be achieved. It seems clear, however, that temporal phasing as well as spatial selectivity would be required to achieve proper control targeted towards random events.

A rather simple version of the above idea is the selective suction technique which combines suction to achieve an asymptotic turbulent boundary layer and longitudinal riblets to fix the location of low-speed streaks. The feasibility of the selective suction as a drag-reducing concept has been demonstrated by Gad-el-Hak and Blackwelder (1989). Low-speed streaks were artificially generated in a laminar boundary layer using the method of Gad-el-Hak and Hussain (1986), and a hot-film probe was used to record the near-wall signature of the streaks. Using a feedforward control loop, an equivalent suction coefficient of C_q = 0.0006 was sufficient to eliminate the artificial events and prevent bursting. This rate is five times smaller than the asymptotic suction coefficient for a corresponding turbulent boundary layer. If this result is sustained in a naturally developing turbulent boundary layer, a skin-friction reduction of close to 60% would be attained.

The recent numerical experiments of Choi *et al.* (1994) also validate the concept of targeting suction/injection to specific near-wall events in a turbulent channel flow. Based on complete interior flow information, their direct numerical simulations indicate a 20% net drag reduction accompanied by significant suppression of the near-wall structures and the Reynolds stress throughout the entire wall-bounded flow. When only wall information was used, a drag reduction of 6% was observed; a rather disappointing result considering that sensing and actuation took place at *every* grid point along the computational wall. In a practical implementation of this technique, even fewer wall sensors would perhaps be available, measuring only a small subset of the accessible information and thus requiring even more sophisticated control algorithms to achieve the same degree of success.

Time sequences of the numerical flow field of Choi *et al.* (1994) indicate the presence of two distinct drag-reducing mechanisms when selective suction/injection is used. First, deterring the sweep motion, without modifying the primary streamwise vortices above the wall, and consequently moving the high-shear regions from the surface to the interior of the channel, thus directly reducing the skin friction. Secondly, changing the evolution of the wall vorticity layer by stabilizing and preventing lifting of the near-wall spanwise vorticity, thus suppressing a potential source of new streamwise vortices above the surface and interrupting a very important regeneration mechanism of turbulence.

3.2 Reactive Feedback Control

Moin and Bewley (1994) categorize reactive feedback control strategies by examining the extent to which they are based on the governing flow equations. Four categories are discerned: adaptive, physical model-based, dynamical systems-based, and optimal control (Figure 1). Note that except for adaptive control, the other three categories of reactive feedback control can also be used in the feedforward mode or the combined feedforward-feedback mode. Also, in a convective environment such as that for a boundary layer, a controller would perhaps combine feedforward and feedback information and may include elements from each of the four classifications. Each of the four categories is briefly described below.

Adaptive schemes attempt to develop models and controllers via some learning algorithm without regard to the details of the flow physics. System identification is performed independently of the flow dynamics or the Navier-Stokes equations which govern this dynamics. An adaptive controller tries to optimize a specified performance index by providing a control signal to an actuator. In order to update its parameters, the controller thus requires feedback information relating to the effects of its control. The most recent innovation in adaptive flow control schemes involves the use of neural networks which relate the sensor outputs to the actuator inputs through functions with variable coefficients and nonlinear, sigmoid saturation functions. The coefficients are updated using the so-called back-propagation algorithm, and complex control laws can be represented with a sufficient number of terms. Hand tuning is required, however, to achieve good convergence properties. The nonlinear adaptive technique has been successfully used by Fan *et al.* (1993) and Jacobson and Reynolds (1993; 1995) to control, respectively, the transition process and the bursting events in turbulent boundary layers.

Heuristic physical arguments can instead be used to establish effective control laws. That approach obviously will work only in situations in which the dominant physics are well understood. An example of this strategy is the active cancellation scheme, used by Gad-el-Hak and Blackwelder (1989) in a physical experiment and by Choi *et al.* (1994) in a numerical experiment, to reduce the drag by mitigating the effect of near-wall vortices. The idea is to oppose the near-wall motion of the fluid, caused by the streamwise vortices, with an opposing wall control, thus lifting the high-shear region away from the surface and interrupting the turbulence regeneration mechanism.

Nonlinear dynamical systems theory allows turbulence to be decomposed into a small number of representative modes whose dynamics are examined to determine the best control law. The task is to stabilize the attractors of a low-dimensional approximation of a turbulent chaotic system. The best known example is the OGY method which, when applied to simpler, small-number of degrees of freedom systems, achieves stabilization with minute expenditure of energy. This and other chaos control strategies, especially as applied to the more complex turbulent flows, will be revisited in Section 4.2.

Finally, optimal control theory applied directly to the Navier-Stokes equations can be used to minimize a cost function in the space of the control. This strategy provides perhaps the most rigorous theoretical framework for flow control. In this method, feedback control laws are derived systematically for the most efficient distribution of control effort to achieve a desired goal. Abergel and Temam (1990) developed such optimal control theory for suppressing turbulence in a numerically simulated, two-dimensional Navier-Stokes flow, but their method requires an impractical full flow-field information. Choi *et al.* (1993) developed a more practical, wall-information-only, sub-optimal control strategy which they applied to the one-dimensional stochastic Burgers equation. Later application of the sub-optimal control theory to a numerically simulated turbulent channel flow is reported by Moin and Bewley (1994).

4. CHAOS CONTROL

4.1 Nonlinear Dynamical Systems Theory

In the theory of dynamical systems, the so-called butterfly effect denotes sensitive dependence of nonlinear differential equations on initial conditions. The solution of such equations may be in the form of a strange attractor whose intrinsic structure contains a well-defined mechanism to produce a chaotic behavior without requiring random forcing. A question arises naturally: just as small disturbances can radically grow within a deterministic system to yield rich, unpredictable behavior, can minute adjustments to a system parameter be used to reverse the process and control, *i.e.* regularize, the behavior of a chaotic system? Recently, that question was answered in the affirmative theoretically as well as experimentally, at least for system orbits which reside on low-dimensional strange attractors (see the review by Lindner and Ditto, 1995). Before describing such strategies for controlling chaotic systems, we first summarize the recent attempts to construct a low-dimensional dynamical systems representation of turbulent boundary layers. Such construction is a necessary first step to be able to use chaos control methods for turbulent flows.

Boundary layer turbulence is described by a set of nonlinear partial differential equations and is characterized by an infinite number of degrees of freedom. This makes it rather difficult to model the turbulence using a dynamical systems approximation. The notion that a complex, infinite-dimensional flow can be decomposed into several low-dimensional subunits is, however, a natural consequence of the realization that quasi-periodic coherent structures dominate the dynamics of seemingly random turbulent shear flows. This implies that low-dimensional, localized dynamics can exist in formally infinite-dimensional extended systems—such as open turbulent flows. Reducing the flow physics to finite-dimensional dynamical systems enables a study of its behavior through an examination of the fixed points and the topology of their stable and unstable manifolds.

In one significant attempt the proper orthogonal, or Karhunen-Loève, decomposition method has been used to extract a low-dimensional dynamical system from experimental data of the wall region (Aubry *et al.* 1988; Aubry, 1990). Aubry *et al.* (1988) expanded the instantaneous velocity field of a turbulent boundary layer using experimentally determined eigenfunctions which are in the form of streamwise rolls. They expanded the Navier-Stokes equations using these optimally chosen, divergence-free, orthogonal functions, applied a Galerkin projection, and then truncated the infinite-dimensional representation to obtain a ten-dimensional set of ordinary differential equations. These equations represent the dynamical behavior of the rolls, and are shown to exhibit a chaotic regime as well as an intermittency due to a burst-like phenomenon. However, Aubry *et al.*'s ten-mode dynamical system displays a *regular* intermittency, in contrast both to that in actual turbulence as well as to the chaotic intermittency encountered by Pomeau and Manneville (1980) in which event durations are distributed stochastically. Nevertheless, the major conclusion of Aubry *et al.*'s study is that the bursts appear to be produced autonomously by the wall region even without turbulence, but are triggered by turbulent pressure signals from the outer layer. More recently, Berkooz *et al.* (1991) generalized the class of wall-layer models developed by Aubry *et al.* (1988) to permit uncoupled evolution of streamwise and cross-stream disturbances. Berkooz *et al.*'s results suggest that the intermittent events observed in Aubry *et al.* do not arise solely because of the effective closure assumption incorporated, but are rather rooted deeper in the dynamical phenomena of the wall region.

In addition to the reductionist viewpoint exemplified by the work of Aubry *et al.* (1988) and Berkooz *et al.* (1991), attempts have been made to determine directly the dimension of the attractors underlying specific turbulent flows. Again, the central issue here is whether or not turbulent solutions to the infinite-dimensional Navier-Stokes equations can be asymptotically described by a finite number of degrees of freedom. Grappin and Léorat (1991) computed the Lyapunov exponents and the attractor dimensions of two- and three-dimensional periodic turbulent flows without shear. They found that the number of degrees of freedom contained in the large scales establishes an upper bound for the dimension of the attractor. Deane and Sirovich (1991) and Sirovich and Deane (1991) numerically determined the number of dimensions needed to specify chaotic Rayleigh-Bénard convection over a moderate range of Rayleigh numbers, *Ra*. They suggested that the *intrinsic* attractor dimension is $O[Ra^{2/3}]$.

The corresponding dimension in wall-bounded flows appears to be dauntingly high. Keefe *et al.* (1992) determined the dimension of the attractor underlying turbulent Poiseuille flows with spatially periodic boundary conditions. Using a coarse-grained numerical simulation, they computed a lower bound on the Lyapunov dimension of the attractor to be approximately 352 at a pressure-gradient Reynolds number of 3200. Keefe *et al.* (1992) argue that the attractor dimension in fully-resolved turbulence is unlikely to be much larger than 780. This suggests that periodic turbulent shear flows are deterministic chaos and that a strange attractor does underlie solutions to the Navier-Stokes equations. Temporal unpredictability in the turbulent Poiseuille flow is thus due to the exponential spreading property of such attractors. Although finite, the computed dimension invalidates the notion that the global turbulence can be attributed to the interaction of a *few* degrees of freedom. Moreover, in a physical channel or boundary layer, the flow is not periodic and is open. The attractor dimension in such case is not known but is believed to be even higher than the estimate provided by Keefe *et al.* for the periodic (*quasi-closed*) flow.

In contrast to closed, absolutely unstable flows, such as Taylor-Couette systems, where the number of degrees of freedom can be small, local measurements in open, convectively unstable flows, such as boundary layers, do not express the global dynamics, and the attractor dimension in that case may inevitably be too large to be determined experimentally. According to the estimate provided by Keefe *et al.* (1992), the colossal data required (about 10^D, where D is the attractor dimension) for measuring the dimension simply exceeds current computer capabilities.

5.2 Chaos Control

There is another question of greater relevance here. Given a dynamical system in the chaotic regime, is it possible to stabilize its behavior through some kind of active control? While other alternatives have been devised (*e.g.*, Fowler, 1989; Hübler and Lüscher, 1989; Huberman, 1990; Huberman and Lumer, 1990), the recent method proposed by workers at the University of Maryland (Ott *et al.*, 1990a; 1990b; Shinbrot *et al.*, 1990; 1992a; 1992b; 1992c; Romeiras *et al.*, 1992) promises to be a significant breakthrough. Comprehensive reviews and bibliographies of the emerging field of chaos control can be found in the articles by Shinbrot *et al*. (1993), Shinbrot (1993; 1995), and Lindner and Ditto (1995).

Ott *et al*. (1990a) demonstrated, through numerical experiments with the Henon map, that it is possible to stabilize a chaotic motion about any pre-chosen, unstable orbit through the use of relatively small perturbations. The procedure consists of applying minute time-dependent perturbations to one of the system parameters to control the chaotic system around one of its many unstable periodic orbits. In this context, *targeting* refers to the process whereby an arbitrary initial condition on a chaotic attractor is steered toward a prescribed point (target) on this attractor. The goal is to reach the target as quickly as possible using a sequence of small perturbations (Kostelich *et al.*, 1993a).

The success of the Ott-Grebogi-Yorke's (OGY) strategy for controlling chaos hinges on the fact that beneath the apparent unpredictability of a chaotic system lies an intricate but highly ordered structure. Left to its own recourse, such a system continually shifts from one periodic pattern to another, creating the appearance of randomness. An appropriately controlled system, on the other hand, is locked into one particular type of repeating motion. With such a reactive control the dynamical system becomes one with a stable behavior. The OGY-method can be simply illustrated by the schematic in Figure 3. The state of the system is represented as the intersection of a stable manifold and an unstable one. The control is applied intermittently whenever the system departs from the stable manifold by a prescribed tolerance, otherwise the control is shut off. The control attempts to put the system back onto the stable manifold so that the state converges toward the desired trajectory. Unmodeled dynamics cause noise in the system and a tendency for the state to wander off in the unstable direction. The intermittent control prevents that and the desired trajectory is achieved. This efficient control is not unlike trying to balance a ball in the center of a horse saddle (Moin and Bewley, 1994). There is one stable direction (front/back) and one unstable direction (left/right). The restless horse is the umodeled dynamics, intermittently causing the ball to move in the wrong direction. The OGY-control needs only be applied, in the most direct manner possible, whenever the ball wanders off in the left/right direction.

The OGY-method has been successfully applied in a relatively simple experiment by Ditto *et al*. (1990) and Ditto and Pecora (1993) at the Naval Surface Warfare Center, in which *reverse chaos* was obtained in a parametrically driven, gravitationally buckled, amorphous magnetoelastic ribbon. Garfinkel *et al.* (1992) applied the same control strategy to stabilize drug-induced cardiac arrhythmias in sections of a rabbit ventricle. Other extensions, improvements and applications of the OGY-strategy include higher-dimensional targeting (Auerbach *et al.*, 1992; Kostelich *et al.*, 1993b), controlling chaotic scattering in Hamiltonian (*i.e.*, nondissipative, area conservative) systems (Lai *et al.*, 1993a; 1993b), synchronization of identical chaotic systems that govern communication, neural or biological processes (Lai and Grebogi, 1993), use of chaos to transmit information (Hayes *et al.*, 1993), control of transient chaos (Lai *et al.*, 1994), and taming spatio-temporal chaos using a sparse array of controllers (Chen *et al.*, 1993; Qin *et al.*, 1994; Auerbach, 1994).

In a more complex system, such as a turbulent boundary layer, there exist numerous interdependent modes and many stable as well as unstable manifolds (directions). Factors that make turbulence control a challenging task are the potentially quite large perturbations caused by the unmodeled dynamics of the flow, the non-stationary nature of the desired dynamics, and the complexity of the saddle shape describing the dynamics of the different modes. Nevertheless, the OGY-control strategy has several advantages that are of special interest in the control of turbulence: the mathematical model for the dynamical system need not be known; only **small** changes in the control parameter are required; and noise can be tolerated (with appropriate penalty).

Recently, Keefe (1993a; 1993b) made a useful comparison between two nonlinear control strategies as applied to fluid problems. Ott-Grebogi-Yorke's feedback method described above and the model-based control strategy originated by Hübler (see, for example, Hübler and Lüscher, 1989; Lüscher and Hübler, 1989), the H-method. Both novel control methods are essentially a generalization of the classical perturbation cancellation technique: apply a prescribed forcing to subtract the undesired dynamics and impose the desired one. The OGY-strategy exploits the sensitivity of chaotic systems to stabilize existing periodic orbits and steady states. Some feedback is needed to steer the trajectories toward the chosen fixed point, but the required control signal is minuscule. In contrast, Hübler's scheme does not explicitly make use of the system sensitivity. It produces general control response (periodic or aperiodic) and needs little or no feedback, but its control inputs are generally large. The OGY-strategy exploits the nonlinearity of a dynamical system; indeed the presence of a strange attractor and the extreme sensitivity of the dynamical system to initial conditions are essential to the success of the method. In contrast, the H-method works equally for both linear and nonlinear systems.

Keefe (1993a) first examined numerically the two schemes as applied to fully-developed and transitional solutions of the Ginzburg-Landau equation, an evolution equation that governs the initially weakly nonlinear stages of transition in several flows and that possesses both transitional and fully-chaotic solutions. The Ginzburg-Landau equation has solutions that display either absolute or convective instabilities, and is thus a reasonable model for both closed and open flows. Keefe's main conclusion is that control of nonlinear systems is best obtained by making maximum use possible of the underlying natural dynamics. If the goal dynamics is an unstable nonlinear solution of the equation and the flow is nearby at the instant control is applied, both methods perform reliably and at low-energy cost in reaching and maintaining this goal. Predictably, the performance of both control strategies degrades due to noise and the spatially discrete nature of realistic forcing. Subsequently, Keefe (1993b) extended the numerical experiment in an attempt to reduce the drag in a channel flow with spatially periodic boundary conditions. The OGY-method reduces the skin friction to 60–80% of the uncontrolled value at a mass-flux Reynolds number of 4408. The H-method fails to achieve any drag reduction when starting from a fully-turbulent initial condition but shows potential for suppressing or retarding laminar-to-turbulence transition. Keefe (1993a) suggests that the H-strategy might be more appropriate for boundary layer control, while the OGY-method might best be used for channel flows.

It is also relevant to note here the work of Bau and his colleagues at the University of Pennsylvania (Singer *et al.*, 1991; Wang *et al.*, 1992), who devised a feedback control to stabilize (*relaminarize*) the naturally occurring chaotic oscillations of a toroidal thermal convection loop heated from below and cooled from above. Based on a simple mathematical model for the *thermosyphon*, Bau and his colleagues constructed a reactive control system that was used to alter significantly the flow characteristics inside the convection loop. Their linear control strategy, perhaps a special version of the OGY's chaos control method, consists simply of sensing the deviation of fluid temperatures from desired values at a number of locations inside the thermosyphon loop and then altering the wall heating either to suppress or to enhance such deviations. Wang *et al.* (1992) also suggested extending their theoretical and experimental method to more complex situations such as those involving Bénard convection (Tang and Bau, 1993a; 1993b). Hu and Bau (1994) used a similar feedback control strategy to demonstrate that the critical Reynolds number for the loss of stability of planar Poiseuille flow can be significantly increased or decreased.

Other attempts to use low-dimensional dynamical systems representation for flow control include the work of Berkooz *et al.* (1993), Corke *et al.* (1994), and Coller *et al.* (1994a; 1994b). Berkooz *et al.* (1993) applied techniques of modern control theory to estimate the phase-space location of dynamical models of the wall-layer coherent structures, and used these estimates to control the model dynamics. Since discrete wall-sensors provide incomplete knowledge of phase-space location, Berkooz *et al.* maintain that a nonlinear observer, which incorporates past information and the equations of motion into the estimation procedure, is required. Using an extended Kalman filter, they achieved effective control of a bursting pair of rolls with the equivalent of two wall-mounted shear sensors. Corke *et al.* (1994) used a low-dimensional dynamical system based on the proper orthogonal decomposition to guide control experiments for an axisymmetric jet. By sensing the downstream velocity and actuating an array of miniature speakers located at the lip of the jet, their feedback control succeeded in converting the near-field instabilities from spatial-convective to temporal-global. Coller *et al.* (1994a; 1994b) developed a feedback control strategy for strongly nonlinear dynamical systems, such as turbulent flows, subject to small random perturbations that kick the system intermittently from one saddle point to another along heteroclinic cycles. In essence, their approach is to use local, weakly nonlinear feedback control to keep a solution near a saddle point as long as possible, but then to let the natural, global nonlinear dynamics runs its course when *bursting* (in a low-dimensional model) does occur. Though conceptually related to the OGY-strategy, Coller *et al.*'s method does not actually stabilize the state but merely holds the system near the desired point longer than it would otherwise stay.

Shinbrot and Ottino (1993a; 1993b) offer yet another strategy presumably most suited for controlling coherent structures in area-preserving turbulent flows. Their geometric method exploits the premise that the dynamical mechanisms which produce the organized structures can be remarkably simple. By repeated stretching and folding of “horseshoes” which are present in chaotic systems, Shinbrot and Ottino have demonstrated numerically as well as experimentally the ability to create, destroy and manipulate coherent structures in chaotic fluid systems. The key idea to create such structures is to intentionally place folds of horseshoes near low-order periodic points. In a dissipative dynamical system, volumes contract in state space and the co-location of a fold with a periodic point leads to an isolated region that contracts asymptotically to a point. Provided that the folding is done properly, it counteracts stretching. Shinbrot and Ottino (1993a) applied the technique to three prototypical problems: a one-dimensional chaotic map; a two-dimensional one; and a chaotically advected fluid.

5. MICROFABRICATION

Manufacturing processes that can create microscopic machinery are termed microfabrications. In this emerging technology, under intensive development only since 1990, electronic and mechanical components are combined on a single silicon chip. Sensors for pressure, temperature, velocity, mass flow or sound are currently combined with motors, electrostatic actuators, pneumatic actuators, pumps, valves, gears or tweezers on single programmable elements of typical size O[100 μ]. Microelectromehanical systems (or MEMS) have been constructed and tested during the last few years at numerous laboratories. The new *Journal of Microelectromehanical Systems* and *Journal of Micromechanics and Microengineering* are dedicated to this technology, and the older *Sensors and Actuators* is increasingly allotting more of its pages to MEMS. Entire sessions in scientific meetings have been increasingly assigned to MEMS applications in fluid mechanics (see, for example, the presentations by McMichael, Tai, Mehregany, Mastrangelo, and Yun, all made at the *AIAA Third Shear Flow Control Conference*, Orlando, Florida, 6–9 July 1993, and the volumes edited by Bandyopadhyay *et el.*, 1994, and Breuer *et al.*, 1996). Recent reviews of the use, or potential use, of MEMS in flow control include those by McMichael (1996), Mehregany *et al.* (1996), Ho and Tai (1996; 1998), and Gad-el-Hak (1999; 2000).

MEMS would be ideal for the reactive flow control concept advocated in the present paper. Methods of flow control targeted towards specific coherent structures involve nonintrusive detection and subsequent modulation of events that occur randomly in space and time. To achieve proper targeted control of these quasi-periodic vortical events, temporal phasing as well as spatial selectivity are required. Practical implementation of such an idea necessitates the use of a large number of intelligent, communicative wall sensors and actuators arranged in a checkerboard pattern. Gad-el-Hak (1994) provides estimates for the number and characteristics of such elements required to modulate the turbulent boundary layer which develops along a typical commercial aircraft or nuclear submarine. An upper-bound number to achieve total turbulence suppression is about one million sensors/actuators per square meter of the surface.

The sensors would be expected to measure the amplitude, location, and phase or frequency of the signals impressed upon the wall by incipient bursting events. Instantaneous wall-pressure or wall-shear stress can be sensed, for example. The normal or in-plane motion of a minute membrane is proportional to the respective point force of primary interest. For measuring wall pressure, microphone-like devices respond to the motion of a vibrating surface membrane or an internal elastomer. Several types are available including variable-capacitance (condenser or electret), ultrasonic, optical (*e.g.*, optical-fiber and diode-laser), and piezoelectric devices (see, for example, Löfdahl *et al.*, 1993; 1994). A potentially useful technique for our purposes has been recently tried at MIT (Haritonidis et al., 1990a; 1990b). An array of extremely small (0.2 mm in diameter) laser-powered microphones (termed picophones) was machined in silicon using integrated circuit fabrication techniques, and was used for field measurement of the instantaneous surface pressure in a turbulent boundary layer.

Actuators are expected to produce a desired change in the targeted coherent structures. The local acceleration action needed to stabilize an incipient bursting event can be in the form of adaptive wall, transpiration or wall heat transfer. Traveling surface waves can be used to modify a locally convecting pressure gradient such that the wall motion follows that of the coherent event causing the pressure change. Surface motion in the form of a Gaussian hill with height y^+ = O[10] should be sufficient to suppress typical incipient bursts (Lumley, 1991). Such time-dependent alteration in wall geometry can be generated by driving a flexible skin using an array of piezoelectric devices (dilate or contract depending on the polarity of current passing through them), electromagnetic actuators, magnetoelastic ribbons (made of nonlinear materials that change their stiffness in the presence of varying magnetic fields), or Terfenol-d rods (a novel metal composite, developed at Grumman Corporation, which changes its length when subjected to a magnetic field). Note should also be made of other exotic materials that can be used for actuation. For example, electrorheological fluids (Halsey and Martin, 1993) instantly solidify when exposed to an electric field, and may thus be useful for the present application. Recently constructed microactuators specifically designed for flow control include those by Wiltse and Glezer (1993), James *et al.* (1994), Jacobson and Reynolds (1995), and Vargo and Muntz (1996).

Suction/injection at many discrete points can be achieved by simply connecting a large number of minute streamwise slots, arranged in a checkerboard pattern, to a low-pressure/high-pressure reservoir located underneath the working surface. The transpiration through each individual slot is turned on and off using a corresponding number of independently controlled microvalves. Alternatively, positive-displacement or rotary micropumps (see, for example, Sen *et al.*, 1996; Sharatchandra *et al.*, 1996) can be used for blowing or sucking fluid through small holes/slits. Based on the results of Gad-el-Hak and Blackwelder (1989), equivalent suction coefficients of about 0.0006 should be sufficient to stabilize the near-wall region. Assuming that the skin-friction coefficient in the uncontrolled boundary layer is $C_f = 0.003$, and assuming further that the suction used is sufficient to establish an asymptotic boundary layer ($d\theta / dx = 0$, where θ is the momentum thickness), the skin friction in the reactively controlled case is then $C_f = 0 + 2\,C_q = 0.0012$, or 40% of the original value. The net benefit will, of course, be reduced by the energy expenditure of the suction pump (or micropumps) as well as the array of microsensors and microvalves.

Finally, if the bursting events are to be eliminated by lowering the near-wall viscosity, direct electric-resistance heating can be used in liquid flows and thermoelectric devices based on the Peltier effect can be used for cooling in the case of gaseous boundary layers. The absolute viscosity of water at 20°C decreases by approximately 2% for each 1°C rise in temperature, while for room-temperature air, μ decreases by approximately 0.2% for each 1°C drop in temperature. The streamwise momentum equation written at the wall can be used to show that a suction coefficient of 0.0006 has approximately the same effect on the wall-curvature of the instantaneous velocity profile as a surface heating of 2°C in water or a surface cooling of 40°C in air (Liepmann and Nosenchuck, 1982; Liepmann *et al.*, 1982).

Sensors and actuators of the types discussed above can be combined on individual electronic chips using microfabrication technology. The chips can be interconnected in a communication network that is controlled by a massively parallel computer or a self-learning neural network. Factors to be considered in an eventual field application of chips produced using microfabrication processes include sensitivity of sensors, sufficiency and frequency response of actuators' action, fabrication of large arrays at affordable prices, survivability in the hostile field environment, and energy required to power the sensors/actuators. As argued by Gad-el-Hak (1994), sensor/actuator chips currently produced are small enough for typical field application, and they can be programmed to provide a sufficiently large/fast action in response to a certain sensor output (see also Jacobson and Reynolds, 1995). Present prototypes are, however, still quite expensive as well as delicate. But so was the transistor when first introduced! It is hoped that the unit price of future sensor/actuator elements would follow the same dramatic trends witnessed in case of the simple transistor and even the much more complex integrated circuit.

6. NEURAL NETWORKS

Biologically inspired neural networks are finding increased applications in many fields of science and technology. Modeling of complex dynamical systems, adaptive noise canceling in telephones and modems, bomb sniffers, mortgage-risk evaluators, sonar classifiers, and word recognizers are but a few of existing usages of neural nets. The book by Nelson and Illingworth (1991) provides a lucid introduction to the field, and the review article by Antsaklis (1993) focuses on the use of neural nets for the control of complex dynamical systems. For flow control applications, neural networks offer the possibility of adaptive controllers that are simpler and potentially less sensitive to parameter variations as compared to conventional controllers. Moreover, if a colossal number of sensors and actuators is to be used, the massively parallel computational power of neural nets will surely be needed for real-time control.

The basic elements of a neural network are input layer, hidden layers and output layer. Several inputs are connected to the nodes (neurons or processing elements) that form the input layer. There are one or more hidden layers, followed by an output layer. Note that the number of connections is higher than the total number of nodes. Both numbers are chosen based on the particular application and can be arbitrarily large for complex tasks. Simply put, the multi-task job of each processing element is to evaluate each of the input signals to that particular element, calculate the weighted sum of the combined inputs, compare that total to some threshold level, and finally determine what the output should be. The various weights are the adaptive coefficients which vary dynamically as the network *learns* to perform its assigned task; some inputs are more important than others. The threshold, or transfer, function is generally nonlinear; the most common one being the continuous sigmoid, or S-shaped, curve, which approaches a minimum and maximum value at the asymptotes. If the sum of the weighted inputs is larger than the threshold value, the neuron generates a signal; otherwise no signal is *fired*. Neural networks can operate in feedforward or feedback mode. Complex systems, for which dynamical equations may not be known or may be too difficult to solve, can be modeled using neural nets.

For flow control, neural networks provide convenient, fast, nonlinear adaptive algorithms to relate sensor outputs to actuator inputs via variable-coefficient functions and nonlinear, sigmoid saturation functions. With no prior knowledge of the pertinent dynamics, a self-learning neural network develops a model for that dynamics through observations of the applied control and sensed measurements. The network is by nature nonlinear and can therefore better handle nonlinear dynamical systems, a difficult task when classical, linear or weakly nonlinear, control strategies are attempted. The feedforward type of neural network acts as a nonlinear filter forming an output from a set of input data. The output can then be compared to some desired output, and the difference (error) is typically used in a back-propagation algorithm which updates the network parameters.

The number of researchers using neural networks to control fluid flows is growing rapidly. In here, we provide only a small sample. Using a pre-trained neural network, Fan *et al.* (1993) conducted a conceptual reactive flow control experiment to delay laminar-to-turbulence transition. Numerical simulations of their flow control system demonstrate almost complete cancellation of single and multiple artificial wave disturbances. Their controller also successfully attenuated a natural disturbance signal with developing wave packets from an actual wind-tunnel experiment. Jacobson and Reynolds (1993; 1995) used neural networks to minimize the boundary velocity gradient of three model flows: the one-dimensional stochastic Burgers equation; a two-dimensional computational model of the near-wall region of a turbulent boundary layer; and a real-time turbulent flow with a spanwise array of wall actuators together with upstream and downstream wall-sensors. For all three problems, the neural network successfully learned about the flow and developed into proficient controllers. However, for the laboratory experiments, Jacobson and Reynolds (1995) report that the neural network training time was much longer and the performance was no better than a simpler *ad hoc* controller that they developed. Jacobson and Reynolds emphasize that alternative neural net configurations and convergence algorithms may, however, greatly improve the network performance.

Using the angle of attack and angular velocity as inputs, Faller *et al.* (1994) trained a neural network to model the measured unsteady surface pressure over a pitching airfoil (see also Schreck *et al.*, 1995). Following training and using the instantaneous angle of attack and pitch rate as the only inputs, their network was able to accurately predict the surface pressure topology as well as the time-dependent aerodynamic forces and moments. The model was then used to develop a neural network controller for wing-motion actuator signals which in turn provided direct control of the lift-to-drag ratio across a wide range of time-dependent motion histories. Most recently, Kawthar-Ali and Acharya (1996) developed a neural network controller for use in suppressing the dynamic-stall vortex that periodically develops in the leading edge of a pitching airfoil. Based on the current state of the unsteady pressure field, their control system specified the optimum amount of leading-edge suction to achieve complete vortex suppression.

8. CLOSING REMARKS

The present article reviewed the important advances in the field of turbulent flow control that took place during the past few years. An attempt has been made to place the field in a unifying framework and to properly categorize the different control strategies. Developments in chaos control, microfabrication and neural networks are making it more feasible to perform reactive control of turbulent flows. Field applications, however, have to await further progress in those three areas. Other less complex control schemes, passive as well as active, are more market ready and are also witnessing resurgence of interest.

As is clear from this brief review, there is no lack of flow control methods to achieve a particular goal for free as well as wall-bounded flows across the entire range of Mach and Reynolds numbers. Ranging from simple to complex, from inexpensive to expensive, from passive to active to reactive, and from market ready to futuristic, the fluid engineer has a great variety of control devices to choose from. Flow control is most effective when applied near the transition or separation points; in other words, near the critical flow regimes where flow instabilities magnify quickly. Therefore, delaying/advancing laminar-to-turbulence transition and preventing/provoking separation can be readily accomplished. To reduce the skin-friction drag in a non-separating turbulent boundary layer, where the mean flow is quite stable, is a more challenging problem.

Market-ready techniques include passive and predetermined active control. Shaping, suction, heating/cooling and compliant coatings can be used to delay transition by an order of magnitude in Reynolds number, and, except for the latter technique, can also be used to prevent boundary layer separation. The use of polymers, microbubbles, riblets and LEBUs can lead to skin-friction reduction in turbulent boundary layers. Numerous other techniques are available to reduce form drag, induced drag and wave drag. Remaining issues for field application of market-ready techniques include cost, maintenance and reliability. Potential further improvements in classical flow control techniques will perhaps involve combining more than one technique aiming at achieving a favorable effect that is greater than the sum. Examples include combining suction or polymer injection with riblets for increased effectiveness and saving. Due to its obvious difficulties, synergism has not been extensively studied in the past but deserves future consideration.

Substantial gains are potentially possible when reactive flow control strategies are used. Particularly for turbulent flows, reactive control requires large number of sensors and actuators and will not be possible until the technology for manufacturing inexpensive, robust microsensors and microactuators becomes available. Autonomous control algorithms and associated computers to handle the required colossal data in real time must also be developed. Further research is needed in dynamical systems theory particularly chaos control, microelectromechanical systems, and alternative neural network configurations, convergence algorithms and distributed flow control. The difficulties are daunting but the potential payoffs are enormous.

In parting, it might be worth recalling that a mere 10% reduction in the total drag of an aircraft translates into a saving of $1 billion in annual fuel cost for the commercial fleet in the United States alone. Contrast this benefit to the annual worldwide cost of perhaps a few million dollars for all basic research in the broad field of flow control. Taming turbulence, though difficult, will pay for itself in gold.

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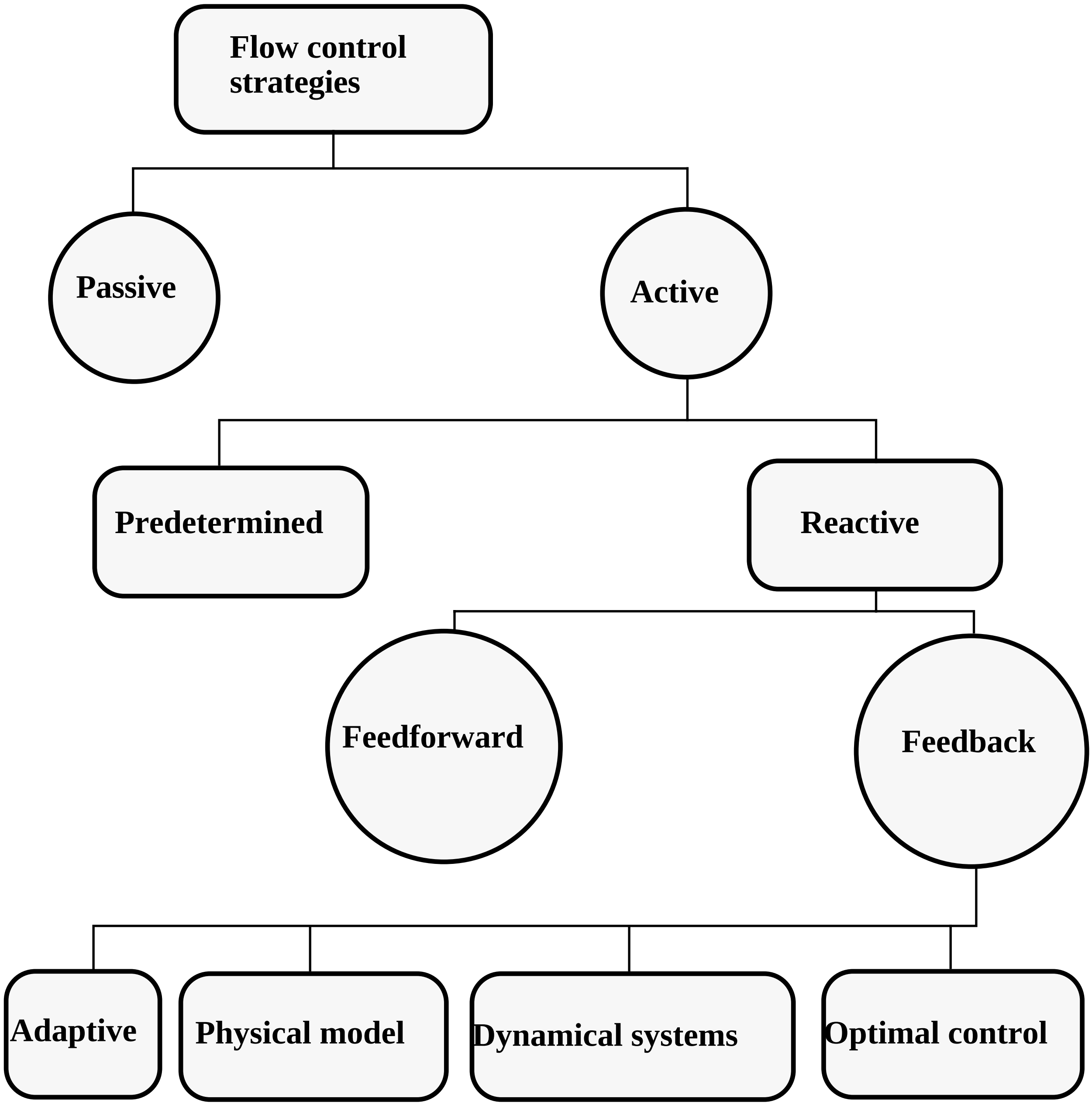

Figure 1. Classification of Flow Control Strategies

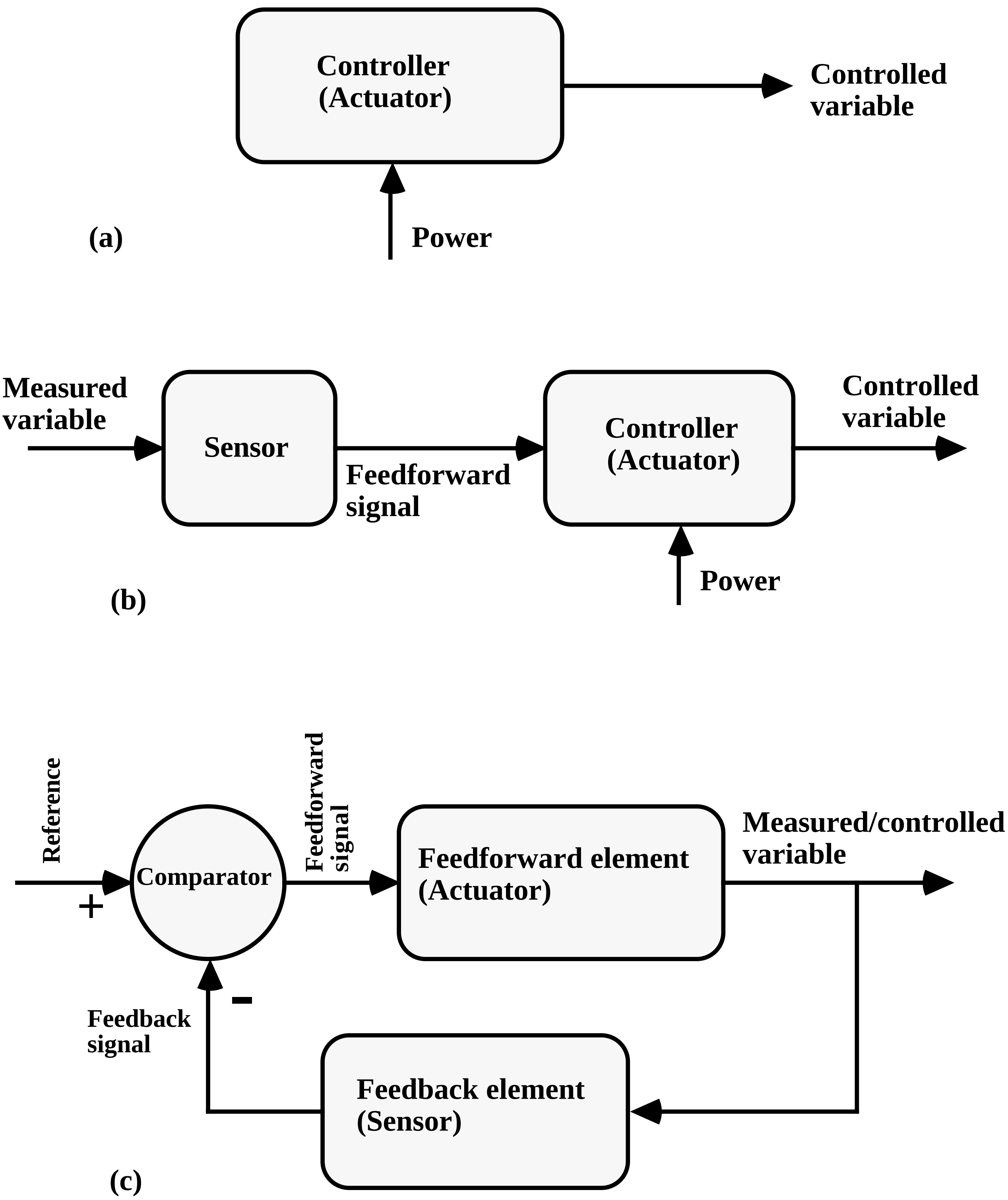

Figure 2. Different Control Loops for Active Flow Control.
(a) Predetermined, Open Loop. (b) Reactive, Feedforward, Open Loop.
(c) Reactive, Feedback, Closed Loop.

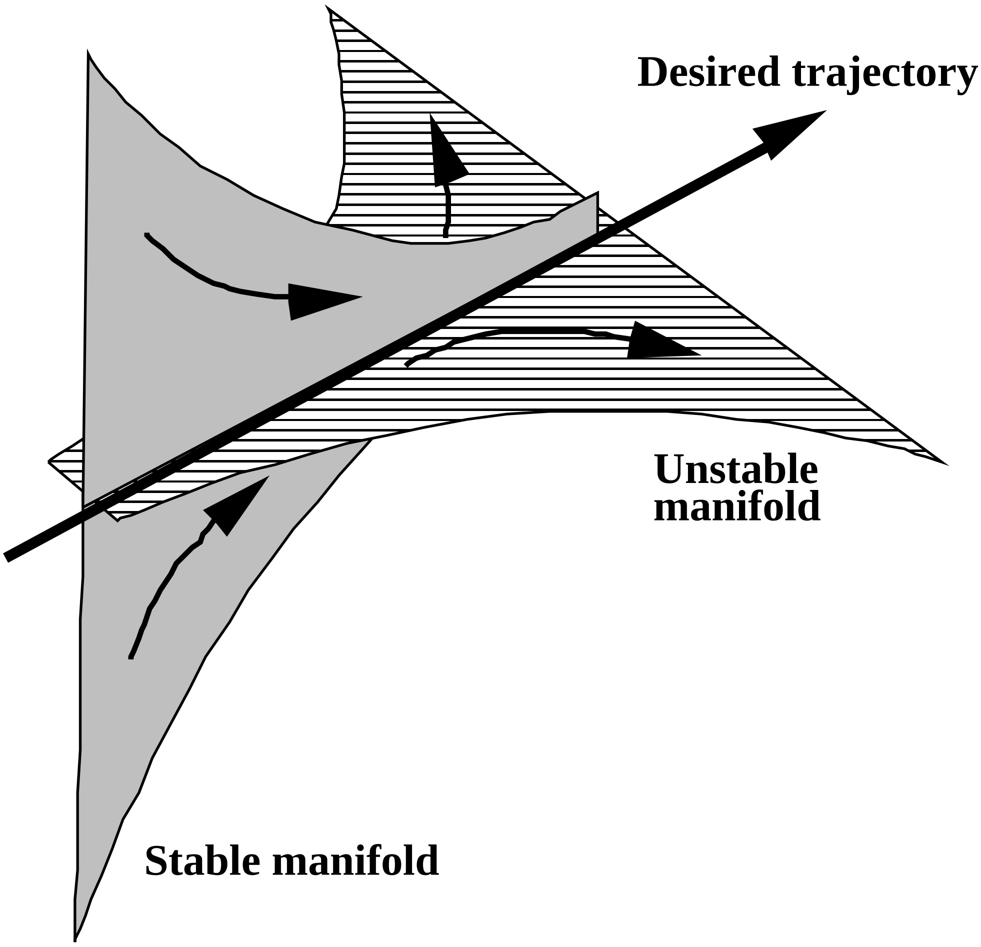

Figure 3. The OGY Method for Controlling Chaos