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ACTIVE FLOW CONTROL: A REVIEW

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Abstract

Flow control have been used for many years to control the fluid flow, and some employ different concepts to serve this purpose in last decades. The ability to manipulate a flow passively or actively is of immense technological importance. This paper is more concentrating on modern active flow control methods. These methods are used majorly to achieve transition delay, drag reduction, lift enhancement, turbulence management, separation postponement, noise suppression, etc. The potential benefits of flow control may include improved performance, affordability, fuel consumption economy, and environmental compliance. A review of major techniques used in this context (with more emphasis on experimental methods) is presented along with a brief discussion on each of them.

Introduction

Active flow-control (AFC) is a fast growing multi-disciplinary science and technology aimed at altering a natural flow state or development path into a more desired state (or path). Flow control research dates back to the discovery of the boundary layer by Prandtl (1904) at the turn of the 20th century. In the period leading up to and during World War II, as well as in the cold war era, flow control was extensively studied and applied, although primarily to military-related flow systems. A comprehensive review and analysis was provided by Lachman (1961) and more recently by Gad-el-Hak et al. (1998), Gad-el-Hak (1998). All known flow control efforts preceding the pioneering work of Schubauer and Skramstad (1947) used steady-state tools and mechanisms for flow management. These are of inherently marginal power efficiency, and therefore limited the implementation of the resulting systems in operational applications. Unsteady flow control using periodic excitation that exploits natural flow instability phenomena such as control of flow separation (Greenblatt and Wygnanski, 2000) has the potential of overcoming the efficiency barrier. As an example, Seifert et al. (1996) showed that separation control using periodic addition of momentum, at a reduced frequency slightly higher than the natural vortex shedding frequency, can save 90–99% of the momentum required to obtain similar gains in performance using steady blowing. The later utilizes the well-known Coanda (1961) effect. The feasibility of increasing the efficiency and simplifying fluid related systems (e.g. high-lift systems) is very appealing if one considers that a 1 percent saving in world consumption of jet fuel is worth about 1.25million dollars a day of direct operating costs (in 2002). Likewise, such fuel savings would lead to reduced environmental impact, although such environmental effects are difficult to quantify. The progress in system integration, miniaturization, actuators, sensors and computational techniques enables the utilization of fast-responding, unsteady, flow-control methods into a closed-loop system. However promising the technology might look, significant barriers exist between the capabilities available to the technologist and the successful application. Comprehensive experiments are required to close the gaps between theory, computations, and real-world applications. These experiments are time consuming and expensive and in many occasions do not produce expected nor repeatable results. Furthermore, progress is achieved frequently by innovation, experience and sheer luck (this is why AFC is sometimes referred to as ‘‘The ART of Flow Control’’). The theory of AFC is of limited scope due to the inherently nonlinear nature of the leading physical processes. Still, significant insight can be gained by considering linear stability analysis of simplified problems, as a first-order approximation helping identify unstable mechanisms that can enhance performance, isolate optimal leading parameter ranges and increase efficiency. Significant progress has been made in control theory for optimal and automated design of closed-loop controllers that can be applied to AFC systems given a sufficiently accurate and efficient model of the system. Likewise, progress made in computer capabilities(processing speed, memory,

storage, and parallel processing)has been accompanied by similar efforts to resolve modeling issues (of turbulence and algorithms) and arrive at efficient and validated numerical tools for unsteady flow computations at relevant Reynolds numbers. However, these efforts are still remote from what the real-world engineering requires, e.g. a trustworthy—at least in terms of providing the right trend solution of unsteady flow control problems on realistic configurations within thirty minutes and setting up a whole new problem within eight hours of work on a state-of-the-art PC or workstation. Before we discuss the basic concepts of AFC, we may briefly explain the overall classification of flow control methods.
Figure 1 shows the classification of flow control methods based on energy expenditure and control loop involved (Kral, 2000).

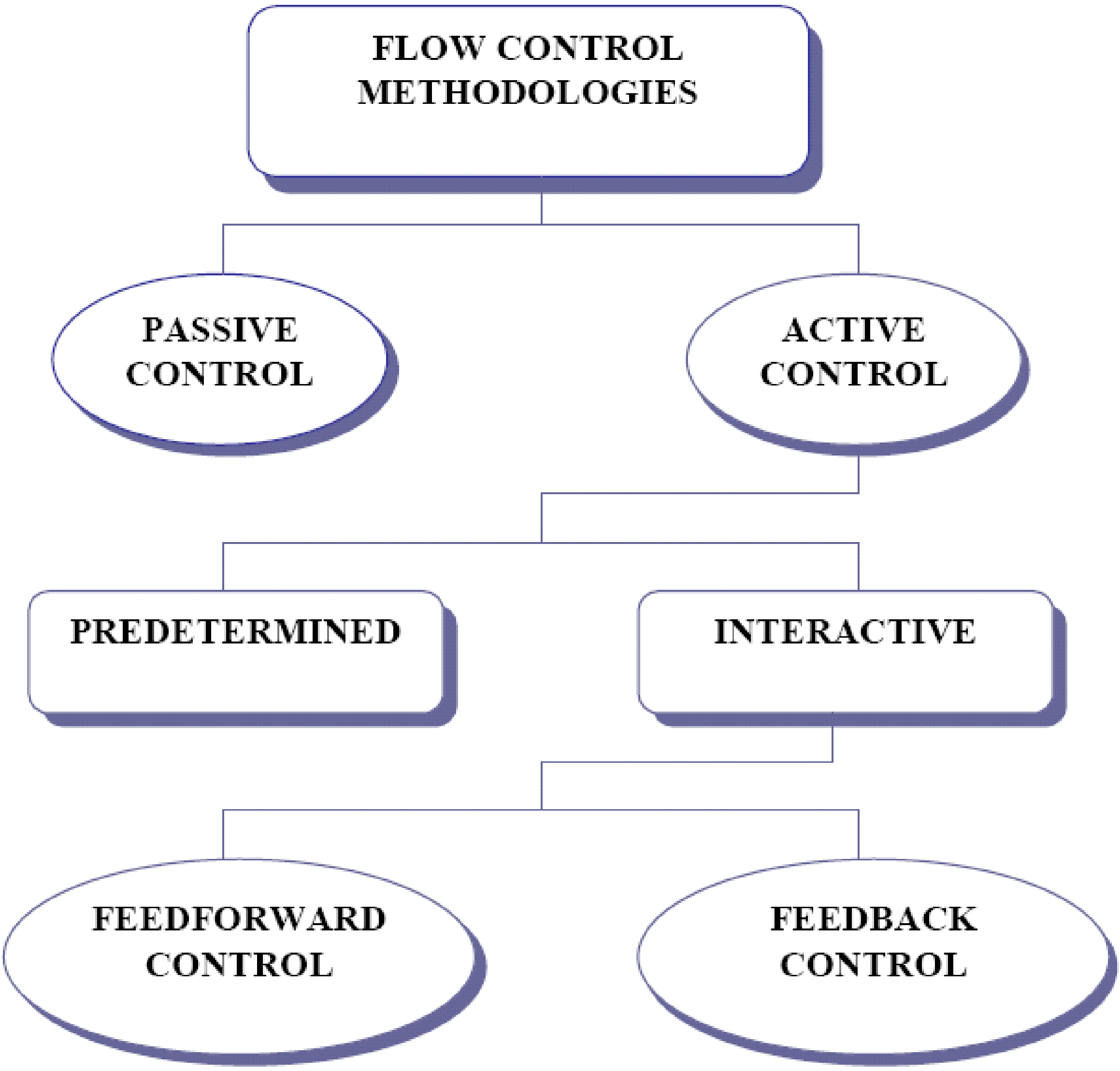

Figure 1: Classification of flow control methods.

As can be seen from the figure the flow control can involve passive or active methods. But during the last decade, more emphasis has been on the development of active control methods in which energy , or auxiliary power, is introduced into the flow. Active control schemes can be divided into predetermined or interactive methods. A predetermined method of control involves the introduction of steady or unsteady energy inputs without consideration for the state of the flow field. Examples of predetermined active flow control include jet vectoring using piezoelectric actuators (Smith and Glezer, 1997) and post-stall lift enhancement and form drag reduction using oscillatory blowing (Seifert and Pack, 1999a). Predetermined open-loop control schemes can be very effective in modifying the flow field.

In interactive methods of flow control, the power input to the actuator (controller) is continuously adjusted based on some form of measurement element (sensor). The control loop for interactive control can be either a feed forward (open) or feedback (closed) loop. In the feed forward control loop, the sensor is placed upstream of the actuator. Therefore the measured flow field parameter and the controlled flow field parameter will differ as flow structures come over stationary sensors and actuators.

Another classification scheme for flow control methods 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 free stream turbulence levels and spectra, gust, and magneto-and electro-hydrodynamic body forces are examples of flow control strategies applied away from the wall.

An important point which we should emphasize is that, there are two primary advantages to active flow control that are not achievable by passive techniques. First, active flow control technology leverages and controls a natural stability of the flow to attain a large effect using small, localized energy input. Control is most effective when the control input is introduced locally at a high receptivity region. For example, the effects of a control scheme can be dramatic when applied near the transition point of a boundary layer flow, the separation point on an airfoil, or the nozzle of a jet. Secondly, active control can be used to control complex, dynamical processes like turbulence production in turbulent boundary layers to reduce skin friction, and hence viscous drag, where the reduction is proportional to the surface area covered by the actuators. The mechanism of turbulence production in boundary layers is understood as a complex series of dynamical events associated with organized, near-wall, low-speed streaks and their instabilities. This process culminates in a sudden eruption, or bursts, of low-momentum fluid away from the wall. As discussed by Bushnell (1985), the correct phasing of the control inputs with respect to the organized flow structures may be the key factor in the success of a control scheme. Lumley and Blossey (1998) present several applications of active control of turbulent flow using the latter approach of modifying the production of turbulence.

Basic concepts

Manipulation of the Navier–Stokes equations advanced the technology associated with continuum fluid dynamics and, via stability analysis, led to the concept of active flow control. However, fundamental discoveries that were crucial to our understanding of turbulent flows inadvertently retarded the development of methods to control them. One such discovery was Reynolds' (1883) famous observation of transition in pipe flows. He differentiated between quiescent (laminar) flow and sinuous (turbulent) flow, and, because the latter seemed to be random, he also separated the instantaneous velocity vector into steady and random components. Time-averaging of the equations (Reynolds averaging) and the resulting Reynolds stresses (Reynolds, 1894), led to a century of study aimed at developing viable predictive techniques based on this viewpoint.

It should be remembered that turbulence represents the natural state of a flow in most flows of engineering significance (e.g., Tennekes and Lumley, 1972): simply consider the flow over any common vehicle, or within any pump, turbine or engine. It is characterized by an irregular three-dimensional, vortical motion that is accompanied by vigorous mixing of the fluid. Mixing is an inseparable ingredient of turbulent flow, because an irregular motion by itself can also occur in solids, particularly compliant ones. The irregularity of the motion implies the existence of a wide spectrum of scales, suggesting that a complete deterministic description of the flow is not attainable. It is hardly surprising, therefore, that turbulence was described in statistical terms that decomposed the velocity and the pressure into mean and fluctuating components. This decomposition created a new set of equations that resemble the instantaneous equations of motion, but which unfortunately cannot be solved unless additional equations for new unknowns created by this decomposition (i.e., the Reynolds stresses) are somehow determined. For many decades, this was the heart of the "turbulence problem" or, as it was often referred to in the literature, the "closure problem." The generation of additional equations from the original Navier–Stokes equations never resolved this dilemma, because it always resulted in a larger number of unknowns than equations being available. It simply shifted the inevitable ad hoc decision to other terms. An entire "modeling industry" that concentrated on providing mathematical models of turbulence evolved over the years. This approach has effectively established Reynolds averaged Navier–Stokes (RANS) methods as the main practical tool available to date, and it is widely used in industrial applications. The success of these models depends to a large extent on the quality of the empirical input that they use. They are therefore capable of "postdicting" the type of flows about which there is a substantial amount of information, rather than "predicting" the behavior of an entirely novel flow.

Since this approach does not explain the physical processes governing turbulent shear flows, nor does it indicate the means of manipulating or controlling such flows, traditional Reynolds averaging is considered to be detrimental to the control of turbulent shear flows. Thus, the most significant discovery of Osborne Reynolds led to a fatalistic approach to the control of turbulence.

In the context of AFC, numerical simulation of the entire flow field by applying finite difference or spectral methods to the instantaneous equations of motion has the potential of becoming a major utility. However, numerical simulation, like an experimental facility, does not delineate the parameters affecting the flow according to their relative significance. It therefore provides results in an indiscriminate fashion, with no insight into the physical aspects governing the flow. However, if the physical parameters affecting the flow are even vaguely understood, then the results provided by direct numerical simulation (DNS) may become a very valuable asset. Indeed, the results of DNS have become a major source of turbulence data that cannot be obtained from experiments.

The most important advance leading to the AFC concept was Prandtl's boundary-layer theory. It separated the flow field into a thin layer of rotational fluid adjacent to a solid surface, surrounded by a large body of irrotational flow that can be considered to be inviscid. The concept describes the flow around streamlined bodies very well, and it also explains the frictional losses and the convective heat transfer occurring between the surface and the adjacent fluid. The major practical simplification stemming from boundary-layer theory is the ability to predict the pressure distribution around a streamlined body using irrotational flow solutions. This also led to the development of the *separation concept*, where the fluid retarded by viscous forces breaks away from the surface as a result of a strong adverse pressure gradient. Experiments supported Prandtl's assumptions and provided criteria for the breakdown of these assumptions due to separation. They also revealed the conditions under which steady, laminar boundary layers develop instabilities and become turbulent. Prandtl's concept provided the framework for the computational viscous/inviscid interaction concept by linking far-field potential-flow solutions with viscous ones at the edge of the boundary layer. Criteria for the stability of the boundary layer and its existence, exemplified by the criteria for separation, followed naturally from this.

Initial extensions of boundary-layer theory to turbulent flow using turbulence models based on Reynolds decomposition hindered progress in AFC, because it suggested that the random motion was determined by local flow conditions and therefore control at a specific location would not carry long-term effects with it. This was also tied to the modeling that was extensively used in engineering applications and that led to the famous statement that "turbulent flow forgets its origin."This belief was deeply engrained until the discovery of large coherent structures in turbulent shear flows. Although the Reynolds-averaged equations are mathematically correct, their applicability is limited to those regions in turbulent shear flows where the turbulence may be assumed to be approximately homogeneous and isotropic. In an intermittently turbulent flow such as exists in the outer part of a turbulent boundary layer, a wake, or a jet, the Reynolds-averaged equations will lump together and indiscriminately average the vortical (turbulent) fluctuations with the irrotational fluctuations existing outside the instantaneous turbulent boundaries of the flow. Corrsin and Kistler (1955) recognized this shortcoming and introduced the concept of a "super layer," which represents a thin, highly contorted boundary separating the turbulent from the irrotational zones. Vorticity is imparted to their rotational fluid along this boundary through the action of viscosity. By assuming that the super layer is continuous without islands of turbulent fluid being present in the irrotational zone, Corrsin and Kistler were able to measure the duration T of the large eddies at the outer edge of the boundary layer, determining that $TU_\infty/\delta \approx 2.5$. This was probably the first measurement delineating the average size of a large eddy propagating at the outer edge of the boundary layer and indicating that turbulence is not as random as it was previously believed to be. Kovasznay et al. (1970) introduced the notion of zone averaging and conditional sampling, which exposed experimentally the limitations of a purely statistical approach to turbulence. Kline et al. (1967) revealed the inhomogeneity existing in the wall region of a turbulent boundary layer, and Blackwelder and Kaplan (1972) demonstrated the coherence of some large-amplitude fluctuations across the entire boundary layer. The most significant observations that gave the impetus to research on coherent structures in turbulence were made by Brown and Roshko (1971,1974) in a two-dimensional mixing layer. Their Schlieren photograph showed that the turbulent mixing layer is dominated by large-scale eddies, which transport within them much smaller and approximately homogeneous turbulent eddies. The mixing-layer spreading rate could clearly be related to the growth of the large eddies, which engulf irrotational fluid from the surrounding streams.

Research on coherent structures in turbulence switched into high gear and dominated experimental and theoretical investigations during the 1970s and1980s. Zone averaging and conditional sampling soon gave way to more sophisticated variable-interval time-averaging (VITA) techniques in which some temporal information relative to a well-recognized event was maintained and used. Experimental methods were altered, with flow visualization and particle image velocimetry (PIV) techniques coming to the foreground because they provide instantaneous information over a large region in the flow rather than detailed temporal information concentrated at a single point. Flow visualization proved to be very helpful in formulating new ideas, and quantitative measurements enabled the researcher to check these ideas. One may realistically expect the technology for an instantaneous and complete mapping of the velocity field become routinely available in the near future.

Extending Reynolds' original idea to the so-called triple decomposition(Hussain and Reynolds, 1970; Reynolds and Hussain, 1972) provides a formalism for tackling the problem of turbulent shear-flow control. The triple decomposition recognizes that the unsteady motion may be decomposed into large, coherent, deterministic structures that are predictable and smaller ones that presently cannot be predicted and are described by statistical methods and therefore presumed to be random. This approach may provide the theoretical tools necessary for controlling the large eddies, and hydrodynamic stability theory, applied to a turbulent flow field, may provide the first step in developing rational models for flow control. Indeed, when inviscid stability theory was applied to the forced turbulent mixing layer (Gaster et al., 1985) it provided good predictions of the relative amplitude and phase distribution across the mixing layer, but rendered only a qualitative prediction of the perturbation amplification in the direction of streaming. One may thus view large coherent structures as a product of interacting instability waves that propagate downstream while either amplifying or decaying during the period of time under consideration, although this view seems to apply best to flows that are inviscidly unstable. Nevertheless, so-called random turbulence also plays a role in determining the quantitative development indicators. Here we have no alternative but to resort to a model of some kind.

The ideas of control and manipulation of turbulent flow originated from the use of a low-level forcing signal that was needed to provide a phase reference for data acquisition that employed a limited number of hot-wire probes, thus giving information at only a select number of locations. It was soon realized that even a low amplitude disturbance alters the mean flow and the intensity and distribution of the turbulent fluctuations (Oster et al., 1978). This led the way to the control of other free shear flows, the control of separation, and the isolation of some basic controlling parameters. In addition, small-scale turbulence proved to be very sensitive to the modes of interaction of the coherent structures, and thus control over instability modes also enables the control of chemical reaction rates, which implies control at the molecular level (Roberts, 1985).

Recent decades have witnessed an unprecedented growth in AFC studies and projected applications. When our ability to control these flows matures, the resulting changes to perceived characteristics of turbulent shear flows will undoubtedly have a major technological impact, as it will alter the dimensions and shapes of wings, diffusers, combustion chambers, ground and under water vehicles, etc. In short, any machinery associated with fluid flow, either external or internal, is bound to look different in the future.

Forty years have passed since flow visualization exposed the existence of large coherent structures in turbulent shear flows. During these years, the direction of turbulence research has changed dramatically from statistical compilation of turbulence intensities and modeling of Reynolds stresses to a search for coherent structures, and from accepting the inevitability of the existence of a "universal" shear flow to manipulation and alteration of that "universality." The time has come to generate some consensus on the subject and present a point of view, which, it is to be hoped, will guide the next generation of graduate students and will slowly filter through the industrial establishment.

One important issue is interrelation of flow control goals which is shown in Figure 2 (Gad-el-Hak, 1998). Let us consider an external wall bounded flow, such as that developing on the exterior surface of an aircraft or a submarine. This kind of flow 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.

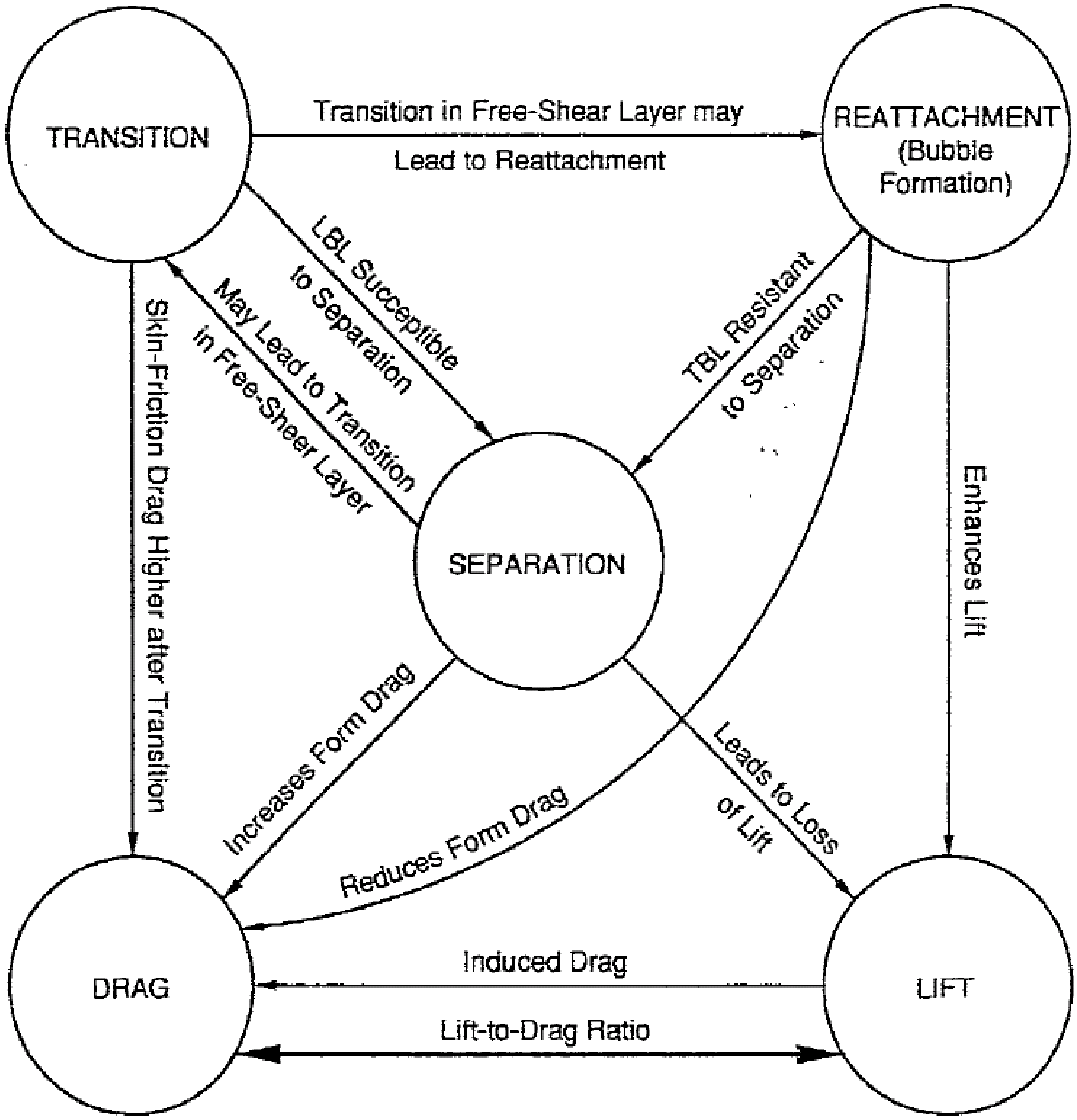

Figure 2: Interrelation between flow control goals.

To focus the discussion further, think of the flow developing on a lifting surface such as an aircraft wing. If the boundary layer becomes turbulent, its resistance to separation is enhanced and more lift could be obtained at increased incidence. On the other hand, the skin-friction drag for a laminar boundary layer can be as much as an order of magnitude less than that for a turbulent one. If transition is delayed, lower skin friction as well as lower flow-induced noise are achieved. However, the laminar boundary layer can only support very small adverse pressure gradient without separation and subsequent loss of lift and increase in form drag occur. Once the laminar boundary layer separates, a free-shear layer forms and for moderate Reynolds numbers transition to turbulence takes place. Increased entrainment of high-speed fluid due to the turbulent mixing may result in reattachment of the separated region and formation of a laminar separation bubble. At higher incidence, the bubble breaks down either separating completely or forming a longer bubble. In either case, the form drag increases and the lift-curve's slope decreases. The ultimate goal of all this is to improve the airfoil's performance by increasing the lift-to-drag ratio. However, induced drag is caused by the lift generated on a lifting surface with a finite span. Moreover, more lift is generated at higher incidence but form drag also increases at these angles.
All of the above points to potential conflicts as one tries to achieve a particular control goal only to adversely affect another goal. An ideal method of control that is simple, inexpensive to build and operate, and does not have any trade-off does not exist, and the skilled engineer has to make continuous compromises to achieve a particular design goal.

Methodology

Active flow control involves the triad of flow phenomena, actuators-sensors, and controls as shown in Figure 3.

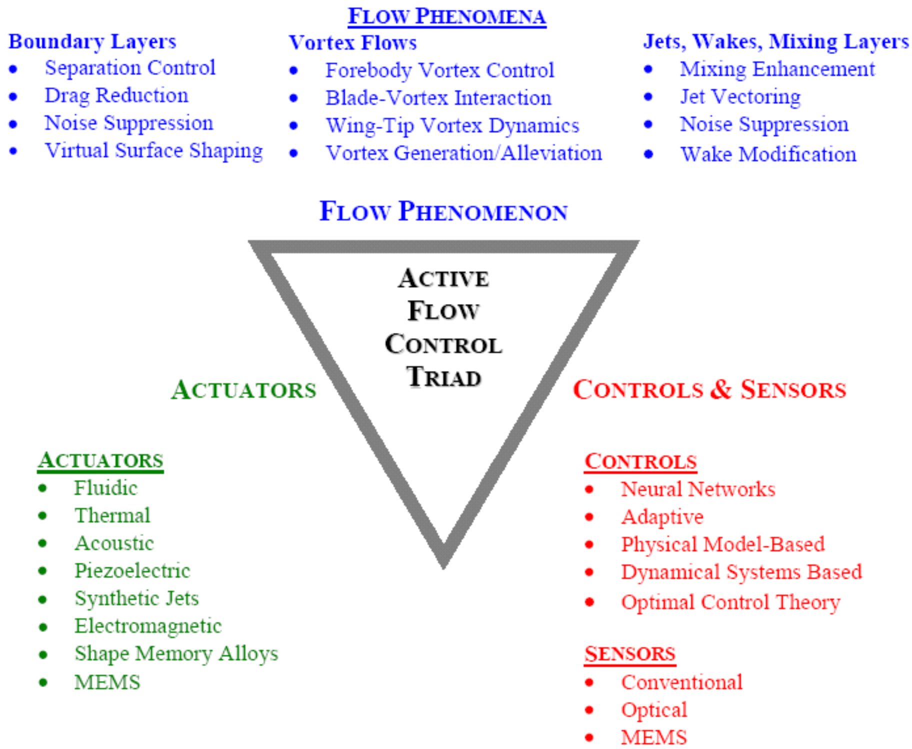

Figure 3: The feedback flow control triad. (Courtesy D. E. Parekh, Georgia Tech Research Institute)

In this figure typical flow phenomena targeted for application of active flow control are listed along with actuators, sensors and methods of control. Bewley (1999) discusses the future of feedback flow control and the need for a renaissance approach where research must be conducted at the intersection of the traditional fields of fluid mechanics, mathematics, and control theory for successful application of feedback control schemes. A consideration of both the fundamental flow physics and the requirements and limitations of control algorithms must be understood.

Flow sensors need to be robust and not significantly alter the flow field that is measured. For practical reasons, most flow sensors for active flow control are flush mounted on a solid surface. At the solid surface, typically wall pressure and/or skin friction can be measured. For situations in which the wall pressure is important, there are many devices for measuring pressure fluctuations, which are essentially small microphones. Some examples of sensors for measuring wall shear stress include floating element sensors, hot films, and shear stress crystals.

There are many types of actuators that can be used in active flow control, as listed in Figure 3. One of the greatest challenges in making active flow control technology practical is the development of robust actuators. Desired characteristics of actuators include low power consumption, fast response, reliability, and low cost. Three different actuator concepts are highlighted below to give a brief overview of the variety of actuators that can be used in flow control. A recent breakthrough in actuator concepts is the synthetic jet actuator developed at Georgia Institute of Technology. A schematic of this actuator is shown in Figure 4. This class of actuators uses an oscillatory surface within a cavity to generate a jet from the flow that is being controlled without the need for mass injection (Smith and Glezer, 1998). The jet shown in Figure 4 was generated with a piezoelectric diaphragm in a periodic manner. Flow enters and exits the cavity through an orifice. On the intake stroke, fluid is drawn into the cavity from the area surrounding the orifice. As this fluid is driven out of the cavity, a shear layer is formed between the expelled fluid and the surrounding fluid. This layer of vorticity rolls up to form a vortex ring. By the time the diaphragm begins to move away from the orifice to pull fluid back into the cavity, the vortex ring has moved far enough away that it is virtually unaffected. Thus a train of vortex rings is created by the actuator. In the mean, the velocity profile appears similar to a steady jet. Actuators of this type have been shown to exert significant control authority in many applications and have the additional benefits of being compact and requiring no flow plumbing. A variety of flow control results have been achieved using the synthetic jet actuator including thrust-vectoring, mixing enhancement, separation control and virtual surface shaping (Smith and Glezer, 1997; Smith *et al.*, 1997; Amitay *et al.* 1997; Amitay *et al.*, 1999; Amitay and Glezer, 1999; Smith *et al.*, 1998, and Smith *et al.*, 1999). These wealth of applications illustrate the great potential for this type of actuator to be applied to air vehicles for aerodynamic control.

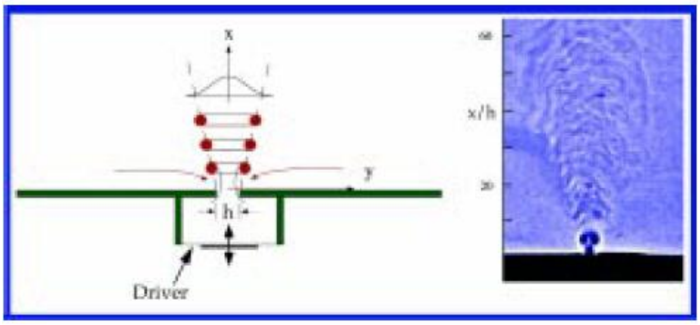

Figure 4: Synthetic jet actuator and flow patterns: (a) schematic and (b) schlieren flow visualization. (Courtesy of B. L. Smith and A. Glezer, Georgia Institute of Technology)

A promising actuator concept recently developed by Cattafesta *et al.* (1999) for cavity noise suppression is shown in Figure 5. This actuator is an improved design over the first generation piezoelectric flaps developed by Cattafesta et al. (1997). The first generation piezo flaps exhibited a tendency to fail mechanically before reaching their respective electrical limitations. The second-generation actuator is used to construct an active, segmented flap at the upstream separation edge of the cavity and is called a monolithic, piezoelectric flap actuator. The separation edge is an appropriate choice for active control devices because it is the location of maximum receptivity.

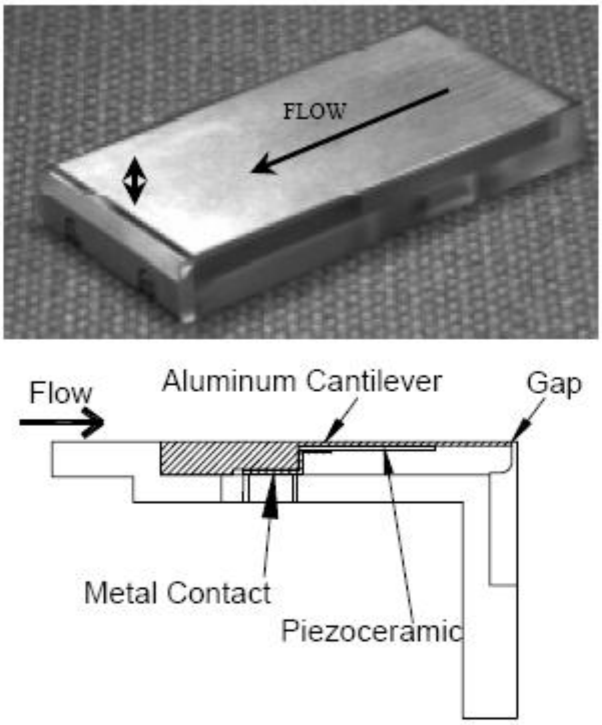

Figure 5: Monolithic piezoelectric flap actuator for suppresion of cavity noise. (Courtesy of L. N. Cattafesta, III, High Technology Corporation)

The third actuator concept highlighted here is a Lorentz-force actuator. Experiments performed by Nosenchuck and Brown (1992), Nosenchuck *et al.* (1995), and Nosenchuck (1996)using a specific electromagnetic forcing have indicated that viscous drag can be reduced by as much as 90%. Flush-mounted Lorentz force actuators are used to induce a current-density field ,**j**, and a magnetic field, **B**, in the vicinity of the wall to provide a three-dimensional body force **L=j x B**. A schematic of a Lorentz force actuator is shown in Figure 6. The actuator is comprised of a pair of subsurface permanent magnets and two surface-mounted. The magnets and electrodes are arranged such that the electric and magnetic fields intersect and create a three dimensional Lorentz force above the actuator. The curl of the Lorentz force represents a source of vorticity. Donovan *et al.* (1997) and Cary *et al.* (1999) have performed a detailed analysis of the vorticity generated over a single EMTC actuator.

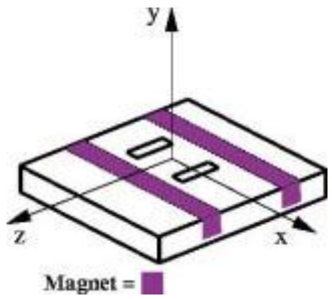

Figure 6: Schematic of a Lorentz force actuator (The smaller rectangles represent surface mounted electrod).

One of the major advances in flow control is the emergence of Micro Electro Mechanical Systems (MEMS) technology, which employs the methods developed for the fabrication of silicon chips to construct very small-scale mechanical devices. The significance of micro machine technology is that it makes it possible to provide mechanical parts of micron size, batch fabricated in large quantities, and integrateable with electronics. Miniaturization to this scale is necessary for both sensors and actuators for successful feedback control of turbulence due to the very small scales of the coherent structures in high-Reynolds-number flows of engineering interest. Miniaturized actuators also simplify the integration of the control system with the overall structure or subsystem. MEMS fabrication processes provide not only miniaturization, but also modular integration of sensors, actuators, and electronics and the affordability enabled by batch processing. However, micro devices for active flow control do not obviate the role of meso devices in flow control technologies. Recent review articles on the use of MEMS for active flow control include McMichael (1996) and Ho and Tai (1996, 1998).

Control application

To successfully apply active flow control, several basic questions should be answered. First the control objective to be achieved is specified (e.g., increased lift). Secondly, the flow phenomenon to be controlled or leveraged is identified (e.g., boundary layer separation). Flow physics is key to scaling and determining influential parameters. An appropriate actuation strategy is then selected (e.g., predetermined open-loop control or feedback control). Finally, a range of operation for the key control parameters is determined (e.g., forcing frequency and amplitude). Several recent successful applications of active flow control are highlighted. The review is intended to provide a sampling of some of the on-going research in this burgeoning area of fluid mechanics. But before elaborating the examples of AFC, the roadmap to apply different control methods is explained.

1. Control of jets

For the reasons like increasing mixing, reduce jet engine noise, and “vector” the jet thrust, there was a lot of interest in the control of jets by means of periodic perturbation. Enhanced mixing is exploited to control heat transfer, chemical reaction rates, and jet plumes (e.g., Rice and Zaman, 1987). For jet noise control, both subsonic and supersonic cases are relevant: for subsonic jets, instability waves do not directly radiate sound, but they do drive the formation of sound-generating turbulence (Moore, 1977); in supersonic jets, it is the instability waves that themselves radiate significant sound (e.g., McLaughlin et al., 1975). In addition, the control of subsonic jets is also believed to have direct consequences for supersonic jets, as the relationship between phase velocity and excitation Strouhal frequency feD/U_0 appear to follow the same general trends observed in subsonic jets (Lepicovsky et al., 1985).(Joslin&Miller). Some examples of jet flow control methods are to follow.
The dynamics of a free round jet subjected to four small pulsed circumferential jets (Pulsating Vortex Generating Jets) have been investigated by Mostafa et al., 1996. The activation of these pulse jets was

shown to enhance the main jet spreading over continuous vortex generator jets. Changing the pulsation frequency and the excitation sequence could be used to control the excitation effectiveness on the main stream. Figure below shows the set up of the experiment.

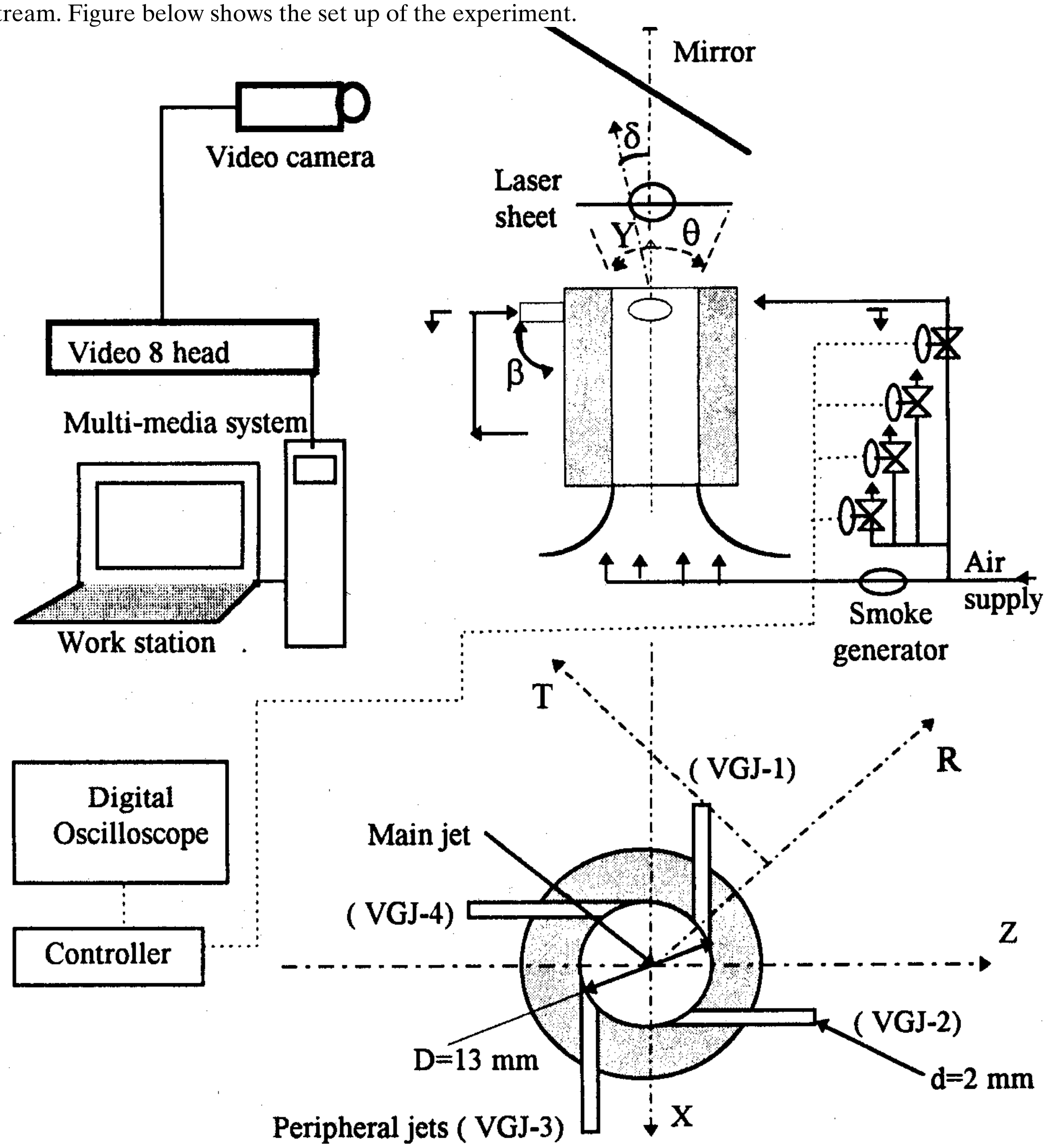

Figure 7: Pulsating jet set up and instrumentation

Flow control techniques for increasing the rate of jet mixing in axisymmetric nozzle flows have been investigated (Behrouzi et al. 2008). A combination of water tunnel and high-speed airflow facilities is used to assess the near-field jet behaviour. Solid tabs, steady fluid tabs (i.e. discrete radially discharged control jets located close to the core jet exit), and pulsed fluid tabs are compared. The effect of fluid tab velocity amplitude, pulse rate, and pulse phase are studied using open loop control. The measurements indicate that fluid tabs generate a similar streamwise vortex formation process (and hence display increased mixing) as previously observed in solid-tabbed nozzle flows. In incompressible testing the mixing effectiveness with a pair of pulsed fluid tabs 180° out-of-phase was as good as a twin solid tab nozzle for a control jet flow ate of only 0.5 percent of the primary (core) jet flow. In preliminary high-speed testing similar benefits of fluid tabs over solid tabs were observed.
Another novel method used by Jahanmiri, 2000 in which a plane subsonic jet was subjected to periodic oscillations in the near nozzle region by a twin vane system. During excitation, the jet was found to spread significantly and entrain mass much more than its steady counterpart. Time averaged static

pressure measured in the flow field with a disc probe exhibited prominent well defined suction regions different from that of a steady jet. The set up is shown in Figure 8.

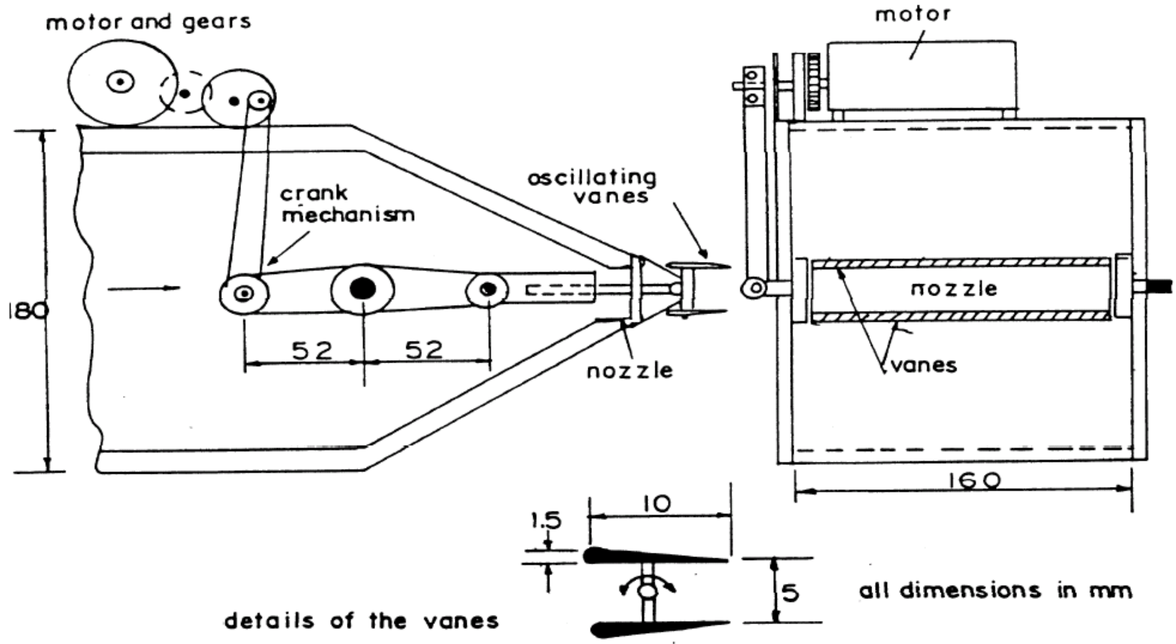

Figure 8: Detail of oscillating vane set up.

Active control of an axisymmetric jet is carried out (Suzuki, et al. 2004) by help of miniature electromagnetic flap actuators which are mounted on the periphery of the nozzle exit to induce various flow modes and enhance mixing processes. It is demonstrated that the flap actuators can significantly modify the large-scale vortical structures. This could be counted as one of the active control method which newly introduced to control the shear flow and associated momentum.

More recently the control of an axisymmetric free jet (Re_{Ue} = 6600) using a single synthetic jet was investigated experimentally (Tamburello & Amitay, 2008). The interaction was examined for a range of momentum coefficients, Strouhal numbers, and synthetic jet orientations (with respect to the main jet). To better explore the complex flow field resulting from the interaction, a rendering technique was used where three-dimensional flow fields were calculated from multiple two-dimensional measurement planes. The synthetic jet deflects the majority of the main jet flow away from it, while drawing some of the flow back toward it. Also, the synthetic jet is shown to appreciably raise the main jet's turbulent quantities, suggesting that mixing has been enhanced. Using triple decomposition, it was shown that the random and coherent motions have similar contributions to the turbulent stresses near the interaction region; whereas the coherent motions prevail farther downstream (and along the shear layers). Measurements of the streamwise vorticity showed that the interaction results in the formation of counter-rotating streamwise vortices, similar to the effect of passive tabs. The size and strength of these structures can be controlled by changing the synthetic jet's momentum coefficient, actuation frequency, or orientation. At low momentum coefficients, the largest effect is obtained for a Strouhal number of 0.32; while at higher momentum coefficients saturation is obtained due to the high excitation level. A steady control jet, which only utilizes the direct impact mechanism, results in vectoring and a deep penetration into the main jet. However, it yields decreased spreading compared to a synthetic jet with the same momentum coefficient.

2. Transition control

Delaying laminar-to-turbulence transition of a boundary layer has many obvious advantages. Depending on the Reynolds number, the skin-friction drag in the laminar state can be as much as an order of magnitude less than that in the turbulent condition. For an aircraft or an underwater body, the reduced drag means longer range, reduced fuel cost and volume, or increased speed. Flow-induced noise results from the pressure fluctuations in the turbulent boundary layer and, hence, is virtually nonexistent in the laminar case. Reducing the boundary layer noise is crucial to the proper operation of an underwater sonar. On the other hand, turbulence is an efficient mixer, and rates of mass, momentum, and heat transfer are much lower in the laminar state; thus, early transition may be sought in some applications as, for example, when enhanced heat transfer rates are desired in heat exchangers or when rapid mixing is needed in combustors.

To delay transition to as far a downstream position as possible, the following steps may be taken. First, because factors that affect the linear amplification of Tollmien–Schlichting waves determine the magnitude of the transition Reynolds number, these waves may be either inhibited or canceled. In the former method of control, the growth of the linear disturbance is minimized by using any, or a combination of the so-called stability modifiers that alter the shape of the velocity profile. These include increased length of favorable pressure gradient, wall transpiration, wall motion, surface heating and cooling, wall curvature, and body forces. Wave cancellation of the growing perturbation is accomplished through exploiting, but not altering, the stability characteristics of the flow. Secondly, the forcing disturbances in the environment in which the laminar shear layer develops may be reduced. This is accomplished by using smooth surfaces, reducing the free stream turbulence and the radiated sound, minimizing body vibration, and ensuring a particulate-free incoming flow or, in case of a contaminated environment such as the ocean, using a particle-defense mechanism. Practically achieved surface smoothness and levels of radiated noise place an upper limit for the unit Reynolds number required for a successful laminar flow-control system. For aircraft, this typically translates into a requirement for high-altitude operation(above 10 km). Thirdly, one may provide a flow where other kinds of instabilities such as Taylor–Görtler vortices or cross flow instabilities, will not occur or at least will not grow at a rapid rate. This is done by avoiding as much as possible concave surfaces or concave streamlines, minimizing the sweep on lifting surfaces, and so forth.(gad el hak, passive, active control)

Liepmann & Nosenchuck, (1982) used an active control method to delay transition. T-S waves (instability waves), can be introduced in a laminar boundary layer by periodic heating of flush-mounted heating elements. Experiments demonstrated that nearly complete cancellation of a T-S wave excited in this way can be achieved by using a second downstream heating element with a suitable phase shift. As one application of the technique, a single element together with a feedback loop activated by measured shear stress has been used to reduce the amplitude of naturally occurring laminar instability waves. A significant increase in the transition Reynolds number has been observed.

A similar study with the objective to control these waves started end of 1997 at ONERA (Gobert et al., 2000). The main goal is to get a better understanding of the mechanism driving the TS waves and to try to develop a technique cancelling or at least reducing considerably them as soon as they start to grow. The experiments are carried out in a low speed wind tunnel equipped with a test section of 300mm high,400mm wide and 1100mm long.

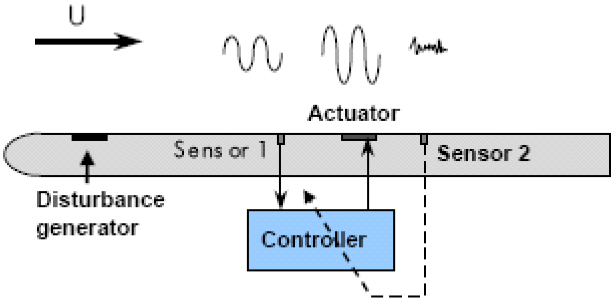

Figure 9: Flat plate instrumentation

An aluminum horizontal flat plate, 780mm long, is installed in the middle of the test section. The instrumentation mounted on the flat plate is shown on Figure 9. A disturbance generator is installed under the surface of the flat plate, near the leading edge, producing a quasi-sine wave of adjustable frequency. This wave is an artificial TS which is convected by the fluid movement. Further the disturbance is measured on the flat plate surface by a sensor (hot film). This signal is used by the controller to detect the wave frequency and to optimize the parameters sent to the actuator in order to cancel the initial disturbance. Downstream of the actuator, a second sensor measures the result of the TS manipulation; this information can be used by the controller to compute a correction factor applied to the process. In first conclusion, the production of TS waves by the use of a generator has been demonstrated by comparison of experimental and computed results. Secondly, a TS control system has been developed, including a reliable set-up and a simplified controller. It has been used in closed loop operation. The control system has demonstrated a good efficiency in different configurations (monochromatic, chromatic waves). The action of the control on different parameters of the instability has been evaluated. The final objective of the TS manipulation is to move the transition back. In this case the transition is not completely located on the flat plate which is too short. Nevertheless the tendency of the transition movement can be estimated by considering the local intermittency factor. This factor is roughly estimated as the ratio of turbulent spot duration over total duration of the signal sample measured by the hot wire probe (0.6 mm from the plate surface) at several stations. The results show that the level of the intermittency factor is reduced by the control which is an indication for delaying the transition point.

A second active method for postponing transition is the application of wall suction. Small amounts of fluid withdrawn from the near-wall region of the boundary layer change the curvature of the velocity profile at the wall and can dramatically alter the stability characteristics of the boundary layer. Additionally, suction inhibits the growth of the boundary layer, and thus the critical Reynolds number based on thickness may never be reached.

Delaying transition using suction is a mature technology, in which most of the remaining problems are in the maintainability and reliability of suction surfaces and the optimization of suction rate and distribution. To protect the delicate suction surfaces on the wing of an aircraft from insect impacts and ice formation at low altitudes, special leading edge systems are used (Wagner and Fischer 1984; Wagner et al. 1984, 1988, 1990). Suction is less suited for underwater vehicles because of the abundance of suspended ocean particulate that can clog the suction surface as well as destabilize the boundary layer.(gad el hak passive active control)

As it is said, surface suction can delay boundary layer transition from laminar to turbulent flow, thus reducing drag on the surface in question. In order for laminar flow control by means of suction to be a paying proposition on aircraft, however, it must reduce total energy consumption as well as net drag. The flow control system that will have the best chance of doing this will use the minimum amount of suction pump energy to achieve a given transition position. Previous work has shown how a steepest descent constrained optimization algorithm in conjunction with a radial basis function gradient estimator is capable of doing this online. Wright and Nelson (2001) used an active control method on a large (2 m chord, 1.6 m span) aerofoil model in a low turbulence tunnel, with variable incidence and direct force measurement. The effect of pressure gradient over the suction section on the efficacy of the suction can therefore be observed, as can the relationship between transition and drag. The system is shown to converge reliably as long as the desired transition is within its range, and to be capable of maintaining control after a change in aerodynamic conditions without needing to re-identify the gradient estimation coefficients.

One of other stability modifiers to be considered here is the addition or removal of heat from a surface, which causes the viscosity to vary with distance from the wall. In general, viscosity increases with temperature for gases, whereas the opposite is true for liquids. With heating in water or cooling in air, the critical Reynolds number is increased, the range of amplified frequencies is diminished, and the amplification rate of unstable waves is reduced. Substantial delay of transition is feasible with a surface that is only a few degrees hotter (in water) or colder (in air) than the free stream. Note that for gases in particular, surface cooling affects both viscosity and density. The increased near-wall density has additional beneficial effects via the stable buoyancy (for certain orientations) and enhanced near-wall momentum it induces.

With cooling, the range of amplified frequencies is diminished and the growth rate of T-S waves is reduced resulting in a substantial increase in transition Reynolds number. These same trends were dramatically confirmed in subsonic and supersonic flights by Dougherty and Fisher (1980) who studied the transition on an airborne cone over the Mach number range of 0.55-2.0. They reported a transition Reynolds number that varied approximately as T_w^{-7} where T_w is the wall temperature. For aircraft, this method of transition delay is feasible only for a vehicle which uses a cryo-fuel such as liquid hydrogen or liquid methane. In that case, a sizable heat sink is readily available. The idea being that the fuel is used to cool the major aerodynamic surfaces of the aircraft as it flows from the fuel tanks to the engines. Reshotko (1979) elaborated the prospects for this method and resulted that, particularly for a hydrogen-fueled aircraft, substantial drag reduction are possible. His calculations showed that the weight of the fuel saved is well in excess of the weight of the required cooling system.

On a heated body of revolution in a high-speed water tunnel, Lauchle and Gurney (1984) observed an increase in transition Reynolds number from 4.5×10^6 to $3.6x10^7$ for an average overheat of 25°C. Clearly, surface heating in water can be an extremely effective method of transition delay and, hence, drag reduction for small, high-speed underwater vehicles where the rejected heat from their propulsion system is used to increase the surface temperature along the body length. The detrimental effects of freestream particulate alluded to earlier are, however, a major obstacle at present for a practical implementation of this method of control. Suspended particulate having a wide-band concentration spectra are abundant in the oceans and ' particledefense7'mechanisms must be sought before using any of the transition delay methods in a contaminated environment.

3. Separation control

Separation delay of a nominally two-dimensional attached boundary layer could be achieved by enhancing the averaged skin friction upstream of the mean separation region. Typically, simply and most effectively, increased skin friction could be achieved by enhanced near wall-outer/core flow (for external and internal flows, respectively) momentum transfer, but many other methods exist, and some would be discussed presently.

At least three known methods exist to enhance near wall streamwise momentum: (1) add (high momentum fluid), (2) remove (low momentum fluid) or (3) re-distribute (momentum across the boundary layer). Emphasis should be placed on minimum energy expenditure in order to re-distribute momentum. Introduction of oscillatory momentum that is coupled with flow instability is typically one to two orders of magnitude more efficient than steady momentum addition for separation control (Figure 10, Seifert et al. 1996). Even intermittent momentum addition, at intervals that are smaller than the typical flow response time is significantly more effective than steady momentum injection. An inherent difficulty arises immediately when searching or high efficiency in maintaining attached turbulent boundary layers that are stable to all known perturbations, with the possible exception of steady streamwise vortices of selected scales. This is a missing enabling technology, identifying and utilizing unstable/least stable modes of an attached turbulent base flow.

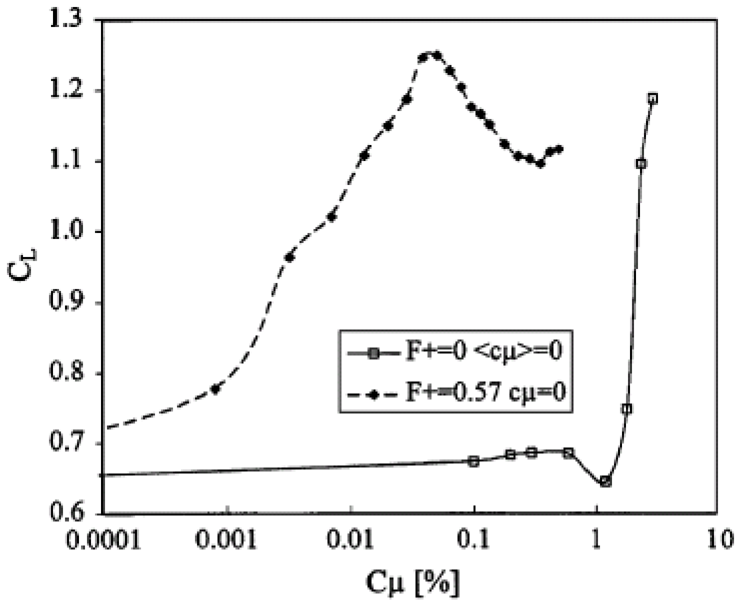

Figure 10: Comparison of oscillatory and steady blowing for post-stall lift-recovery of a NACA 0015 at, R_c=300,000

Here is a partial list of known separation delay techniques. A detailed discussion can be found in Gad-el-Hak et al. (1998). Proper aerodynamic shaping can allow the tailoring of gradual favorable streamwise pressure gradient for laminar-turbulent transition delay. The use of this approach however, is limited by the need to close the aft-body, accompanied by the associated adverse pressure gradient. It is always desirable to tailor the geometry and the pressure gradient such that transition will take place just upstream of the natural mean separation location (in the absence of transition) or at least promote/control transition and enhanced mixing above the separation bubble.

Shaping, transpiration, slot suction, wall-jets, heat transfer and moving walls are just a partial list of proven methods for separation delay. All methods mentioned above rely on enhanced near-wall momentum (see e.g., Lachman (1961) and Gad-el-Hak et al. (1998) & Gad-el-Hak (1998)).

Local or distributed steady suction is a well known and effective method for separation delay, especially when the flow related aspect is of prime importance. However, if overall efficiency and maintenance issues are included in the decision making process, the appeal of steady suction is lowered (Lachman (1961)). Other techniques include vortex generators (mechanical, pop-out, fluidic, and zero-mass-flux) which are effective streamwise vorticity generators that, in turn, mix across the boundary layer and delay separation. Periodic excitation could also be used to enhance skin friction, but 3D unstable modes should be sought to perform this task as 2D excitation is significantly attenuated in zero and slightly adverse pressure-gradient turbulent boundary layers (see e.g., Seifert &Pack (2002)).

Enabling technologies that can assist in enhancing skin friction should provide order 0.1 to 1.0 velocity ratio effectors (i.e. actuators with sufficient control authority).The search for low penalty methods (i.e. methods that cause little or no disturbance while inactive, but with sufficient control authority and low energy consumption) could be combined with working on the verge of separation (i.e. skin friction approaching zero,(Elsberry et al. (1997)).

Separation delay might require distributed sensing, as incipient separation is a local phenomenon. The actuators selected to achieve the desired target, the required power and the control logic are all open issues. Again, effectiveness could be greatly enhanced if flow instability is used to mix across the boundary layer to enhance skin friction.

4. Wake vortex control

A wide variety of aerodynamic and hydrodynamic means for suppressing vortex sheddingis classified into three categories in accordance with the phenomenological mechanism of vortex shedding. The three categories are as follows:(i) surface protrusions, which affect separation lines and/or separated shear layers, e.g. helical strakes, wires, fins, studs or spheres, etc. ;(ii) shrouds, which affect the entrainment layers, e.g. perforated, gauze, axial-rod, axial-slat, etc.;(iii) near wake stabilizers, which prevent interaction of entrainment layers, e.g. splitter plates, guiding vanes, base-bleed, slits cut across the cylinder, etc. Most means in the first two categories are omnidirectional, i.e. they are effective irrespective of the direction of fluid velocity. Some means in the first and all in the third category are unidirectional, i.e. they are effective only for one velocity direction.

The active concept most commonly advocated to reduce the wake hazard is to force instabilities in trailing vortices by oscillating control surfaces periodically such that the integrated aerodynamic loads do not fluctuate. This accelerates unstable vortex growth such that the vortices ultimately interact, pinch-off, and degenerate into harmless small-scale turbulence (Chevalier, 1973;Crouch, 1997; Crow, 1970; Crow and Bate, 1976). On rotorcraft, a major source of noise and vibration arises from a rotor blade cutting through the tip vortex shed by its predecessor (blade-vortex interaction, BVI). Active methods seek to increase the “miss distance” between the rotor blade and tip vortex or diffuse the vortex, for example using trailing-edge flaps. In contrast to passive methods that rely on deflection of conventional control surfaces, AFC seeks to manipulate the vortices by controlling the vortex sheet locally. AFC can be considered as a means of controlling the primary characteristics of vortices, namely their location (centroids), strength, size, and associated velocity components.

The importance of developing control methods for flow over 3D bodies such as a truck or bus is emphasized by Choi et al.(2008). In this body type, vertical structures in the wake significantly change depending on the streamwise length of the body (which may determine the momentum thickness at separation), aspect ratio (i.e., height to width), body height from the ground, and so forth.

5. Drag reduction

Drag reduction is a subject that is explicitly or implicitly interwoven in every aspects of flow control.. The practical benefits of achieving even a modest reduction in fluid resistance to moving bodies are enormous. There is no shortage of ideas on how to reduce the drag. Many challenges remain, however, when attempting to apply laboratory curiosities to real-life situations. For airplanes and submarines, streamlining has led to significant reduction in the pressure drag component attributed to separation. That is not the case for most land vehicles which, despite substantial improvement during the last few decades, are still more or less blunt bodies. Natural laminar flow (NLF)and laminar flow control (LFC) make it possible to have aircraft wings with substantial laminar regions and thus to benefit from the lower skin friction associated with this flow regime. Several techniques like polymer injection, LEBUs, and riblets can educe the skin friction in turbulent boundary layers, but there are certain obstacles for the widespread use of any of these methods. Polymers, in spite of their very impressive percentage drag reduction and their successful application to internal flows, are not sufficiently inexpensive and require large volume for their storage onboard ships and submarines. Riblets lead to very modest drag reduction, and LEBUs are not effective at high Reynolds numbers. Newer strategies such as the random roughness of Sirovich and Karlsson (1997) or the large-scale vortex generators of Schoppa and Hussain (1998) still require more validation—particularly at field Reynolds numbers. The grand problem remains to find a practical, cost-effective method to reduce the turbulent skin-friction drag encountered on the long fuselage of commercial aircraft or of water vessels.

Nature provides numerous instances in which drag reduction is essential for the survival of many species of air and marine animals (Bushnell and Moore 1991). Here, we cite instead two examples of the importance of minimizing the drag of man-made vehicles. At present, the annual fuel cost for all commercial airlines in the United States is about $10 billion—an expenditure that, thanks to declining oil prices adjusted for inflation, has not changed much in over a decade (Hefner 1988; Bushnell 1998). At subsonic cruising speeds, approximately half of the total drag of conventional takeoff and landing aircraft is due to skin friction. Hence, a reduction in skin-friction drag of 20% translates into an annual fuel saving of $1 billion. Not only is this a substantial sum, but many also believe that a return of the 1973 energy crisis is inevitable (Phillips 1979; Kannberg 1988). Although the world may have another 100-year supply of natural petroleum, it is estimated that the supply of the United States will be virtually exhausted early in the next century (Nagel, Alford, and Dugan,1975). Fuel conservation is certainly an important tool to ward off future shortages.

A stated goal of the United States National Aeronautics and Space Administration(NASA) is to improve the lift-to-drag ratio of the commercial fleet of aircraft by a factor of two during the next two decades. This will maintain the competitive edge that the U.S. aerospace industry now enjoys over European and Asian manufacturers. Doubling L/D would have to be done with a combination of clever drag reduction and high-lift devices. There is no shortage of ideas, but application to the real world is another matter altogether (Bushnell 1998; Perrier 1998). For example, to be acceptable to an airline, a drag-reducing device must not add too much weight to the aircraft because this causes a proportional drag increase, must not be too expensive because this increases the capital cost, and must not interfere with maintenance by either compromising safety or increasing operational cost. The second example is from the military sector. The amount of propulsive power available for an underwater vehicle is limited by the volume allocated to its power plant and the efficiency of the various propulsive components. For these vehicles, about 90% of the total drag is due to skin friction. Accordingly, a reduction in skin friction drag of 20% translates into an increase in speed of 6.8%. Although modest, this extra speed may be vital for the survival of a submarine being chased by another underwater vehicle.

Attempts to reduce drag go back to antiquity. Streamlining and other related control methods can eliminate most of the pressure drag due to flow separation. Some form drag remains, however, even when the flow continues to be attached to the trailing edge. Owing to the displacement effects of the boundary layer, the pressure distribution around the body differs from the symmetric distribution predicted by potential flow theory. This remnant drag can be reduced by keeping the boundary layer as thin as possible.

For a blunt body, passive and active methods to reduce wake momentum deficit are available. For missiles, for example, the base drag component—with no jet flow at the base—can be as much as 50% of the total drag. In general, compared with two dimensional bodies, the base drag penalty is lower for axisymmetric bodies because the vortex shedding process is much less intense in the latter case. Base drag is also generally lower at supersonic speeds inasmuch as compressibility effects tend to suppress vortex shedding. At moderate Reynolds numbers, Strykowski and Sreenivasan (1990) have demonstrated that placing a tiny cylinder in just the right place along-side and well outside the wake of a much larger circular cylinder can significantly suppress vortex shedding from the mother cylinder and thus reduce its drag.

Boundary-layer tripping for advancing transition, trailing-edge splitter plate for disrupting the vortex formation process, base cavities, ventilated cavities, locked-vortex afterbodies, multistep afterbodies, and afterbodies employing non axisymmetric boat-tailing concepts are among the passive techniques to modify the flow field around a bluff body. Viswanath (1995) provided a comprehensive review of these passive methods for subsonic and supersonic flows around two-dimensional and axisymmetric bodies. Among the active techniques to increase base pressure and thus to reduce pressure drag are transpiration and vibration. Continuous or pulsating base bleed is used to modify the flow in the separated region. The latter, with zero net mass addition, has been shown to be very effective when pulsating at twice the Karman shedding frequency (Williams and Amato 1989).

Wave resistance and induced drag can also be reduced by geometric design. By sweeping the wings of a subsonic aircraft, drag divergence is delayed to higher Mach numbers, thus allowing the aircraft to fly at higher speeds without experiencing a sudden increase in drag. Additionally, the so-called area rule or coke-bottle effect typically leads to a factor of two reduction in wave drag at Mach number of one(Whitcomb 1956). For surface ships, for which typically half the drag is due to wave resistance, bow and stern bulbs can reduce the energy dissipated into waves at the air–water interface. An even simpler solution to reduce wave drag is to operate the ship well below the hull design speed, as is the case for supertankers.

The induced drag of an aircraft's wing, about 25% of the airplane's total drag at subsonic cruising speeds, is inversely proportional to its aspect ratio and, hence, a lifting surface is typically designed with as large an aspect ratio as permissible by structural considerations and desired degree of maneuverability. End plates or other vortex diffusers can also be used to reduce the induced drag further. In December1986, the *Voyager* aircraft completed the first nonstop, non refueled flight around the world. The primary design goal was to use fuel sparingly to sustain the 9-dayflight. Several innovations contributed to this success, including the use of lightweight graphite honeycomb composites; unique wing, propeller, and body design; and a high-specific-energy, air-cooled power plant. But, additionally, the unusually large wingspan used (33.8 m, including the winglets) contributed to a significant reduction in induced drag and proportional fuel saving. The *Daedalus* became in 1988 the first man-powered, heavier-than-air vehicle to sustain flight for a distance of 110 km. Here, too, a wing with a large aspect ratio and ultra-light-weight material contributed to the record-breaking flight.

Most of the current research efforts are directed toward reducing the skin-friction drag, and this topic will occupy the remainder of this chapter. According to Bushnell (1983), the leverage in this area of research is quite considerable and justifies the study of unusual or high-risk approaches on an exploratory basis.

Modern practical examples

Application of modern flow control to current and next generation air vehicle systems, automotive engineering and propulsion technology will be illustrated by few examples.

1. Air vehicle systems

Airfoil performance enhancement by delaying flow separation, development of practical actuators, scaling from laboratory to prototype, attempts to make the transition to flight vehicles, and drag reduction are described in the following paragraphs. Two themes underlie complexity of the flow physics and improved actuator technology.

Much of the early work on airfoil separation control with unsteady actuation used acoustic waves as the actuator. It was known that sound at certain frequencies would promote boundary-layer transition, so researchers hoped that the boundary layer on airfoils would be sufficiently receptive to acoustic waves to delay both flow separation and stall. As early as 1961, Chang demonstrated the use of acoustic actuation to achieve a 20% reduction in drag on a low-Reynolds-number (Re_c = 80,000) airfoil, with a 19:1 power-savings-to-cost ratio. Collins and Zelenevitz (1975) used sound from an external source to excite and reattach the separated flow on an airfoil at high angles of attack. Internal acoustic actuators acting through slots on the airfoil surfaces were shown by Huang et al.(1987) and Hsiao (1990) to be effective actuators. Acoustic waves emanating from slots were early examples of zero-net-mass actuators. It was shown by Williams et al. (1991) that the physical process by which the internal acoustic actuation influenced the flow was not purely acoustic, but that the unsteady momentum addition to the flow through the mass-displacement effect of the actuator was a primary mechanism responsible for the separation control.

Oscillating-flap actuators were used by Katz et al. (1989) to reattach a separated shear layer to a deflected plate. Delay of separation from a wing's flap was demonstrated by Nishri and Wygnanski (1998) using periodic excitation with a pulsed-blowing actuator. They determined that that required to reattach a separated flow was much lower than that needed to maintain an attached flow, which provided additional evidence for the coexistence of multiple instabilities. A comparison of the actuation amplitudes required to maintain an attached flow on a flapped NACA 0015 airfoil was made by Seifert et al. (1993, 1996). They showed that unsteady actuation amplitudes required an order of magnitude less momentum than steady-flow actuation.

Active flow control by means of periodic suction and blowing as well as pulsed blowing into the flap boundary layer has been applied to a three-element high lift configuration (Gunther et al. 2007). Experimental and numerical investigations have shown that the flow field can be successfully controlled. Leading edge separation on the flap can be delayed and the lift can significantly be enhanced. At Reynolds numbers between 0.3×10^6 and 1×10^6 the flow is influenced by periodic blowing or periodic blowing/suction through slots near the flap leading edge. The delay of flow separation by periodic vertical excitation could be identified in the experiments as well as numerical simulations based on the Unsteady Reynolds-averaged Navier-Stokes equations (URANS). As a result, the mean aerodynamic lift of this practically relevant wing configuration could be significantly enhanced. Figure 11 shows the actuator assembly for this experiment.

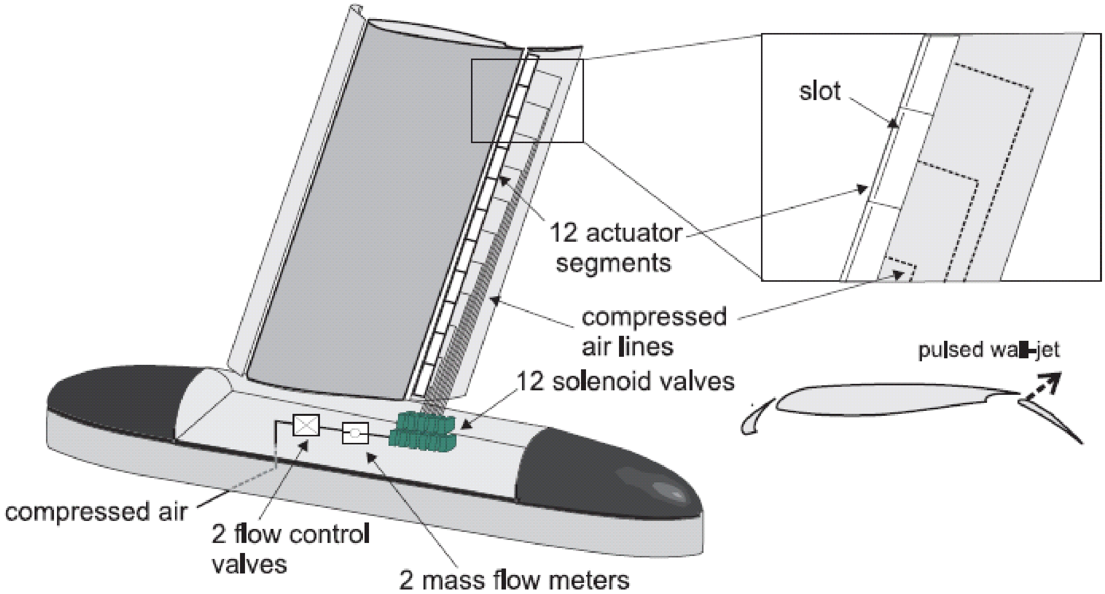

Figure 11: The actuator assembly

A large part of the progress toward practical AFC during the 1990s resulted from improved actuator technology. Historically, the first demonstration of zero net-mass actuation should be attributed to the flow-visualization experiments by Ingard and Labate (1950). They showed that a closed-system (voice-coil type) actuator produces a series of ring vortices, while entraining fluid to form a jet without the need for an external supply of fluid. These zero-net-mass actuators add significant amounts of mean and unsteady momentum to the flow, which is useful for control and even thrust purposes.

The development of small, lightweight, high-bandwidth actuators made it possible to achieve AFC on the timescale of the flow instability. In particular, the invention of the "synthetic jet" actuator by Smith and Glezer (1994, 1998) provided the conveniences of no external source of fluid, compact size, and high band width. The effectiveness of such actuators in a variety of applications has been reviewed by Glezer and Amitay (2002). Today, numerous actuators exist, including MEMs actuators, piezoelectric flaps, pulsed-jet siren valves, and plasma type actuators. Each has its own specific strengths and weaknesses, depending on the specific AFC application.

The complexity of the flow physics associated with AFC becomes apparent when one attempts the transfer from laboratory experiments to prototype applications. Issues of proper scaling of amplitudes, frequencies, and actuator power must be resolved. Wygnanski (2004) provides a detailed discussion of the physics of separation control, highlighting important effects related to amplitudes of actuation. The differences between "separation control" and "circulation control" and their dependence on actuator amplitude are explained for active flow control. For example, a separated region on an airfoil may be eliminated with low levels of actuation($C_\mu < 0.1\%$); then, with a fully attached flow, the airfoil will provide lift at a value close to that predicted by potential-flow theory. When the actuation amplitude is then increased even more, the overall circulation of the airfoil may be increased beyond the ideal flow prediction, a technique known as circulation control.

The use of flow control techniques to reduce skin-friction drag is another important topic for the aerospace engineering community, motivated by the high percentage of fuel burned by commercial aircraft to overcome friction drag. One approach is to *delay boundary-layer transition* by using compliant surfaces or polymer bleed, Tollmien–Schlichting wave cancellation, or stabilization by modification of the mean velocity profile.

One of the most promising approaches for reducing drag on a swept wing is in fact a passive flow technique used to control cross flow instabilities. The concept, introduced by Saric and Reed (2002, 2003), uses micrometer-sized discrete roughness elements along the leading edge of swept wings to trigger short-wavelength instabilities. The seeded short-wavelength instabilities grow to amplitudes where nonlinear mechanisms prevent energy transfer to the more unstable longer-wavelength modes, resulting in an overall delay of the transition on swept wings. The viability of the approach was demonstrated in wind tunnels and proven in flight tests with swept wing sections. Clearly, without a

thorough understanding of the physics of cross flow instability, such an approach would not have been possible.
However, once the boundary layer is turbulent, a different approach is needed, such as a modification of the turbulence production mechanism. Using AFC to suppress the turbulence production mechanism with closed-loop control architectures is an active topic of research in the computational fluid dynamics and control communities, and more will be said about this later. On the experimental side, Rathnasingham and Breuer (2003) were successful in reducing shear-stress using feedback control strategies. Using hot-wire shear-stress sensors and flush-mounted zero-net-mass actuators, they were able to reduce wall pressure fluctuations by15% and viscous shear stress by 7% in a turbulent boundary layer.

2. Automotive engineering

Aerodynamic drag is the cause for more than two-thirds of the fuel consumption of large trucks at highway speeds. Due to functionality considerations, the aerodynamic efficiency of the aft regions of large trucks was traditionally sacrificed. This leads to massively separated flow at the lee side of truck trailers, with an associated drag penalty: roughly a third of the total aerodynamic drag. Active Flow Control (AFC), the capability to alter the flow behavior using small, unsteady, localized energy injection, can very effectively delay boundary layer separation. By attaching a compact and relatively inexpensive "add-on" AFC device to the back side of truck trailers (or by modifying it when possible) the flow separating from the truck trailer could be redirected to turn into the lee side of the truck, increasing the back pressure, thus significantly reducing drag.
A comprehensive and aggressive research plan that combines actuator development, computational fluid dynamics and bench-top as well as wind tunnel testing was performed by Seifert et al (2008). The research uses an array of 15 newly developed suction and oscillatory blowing actuators housed inside a circular cylinder attached to the aft edges of a generic 2D truck model. Preliminary results indicate that a net drag reduction of 10% on full-scale trucks is achievable.

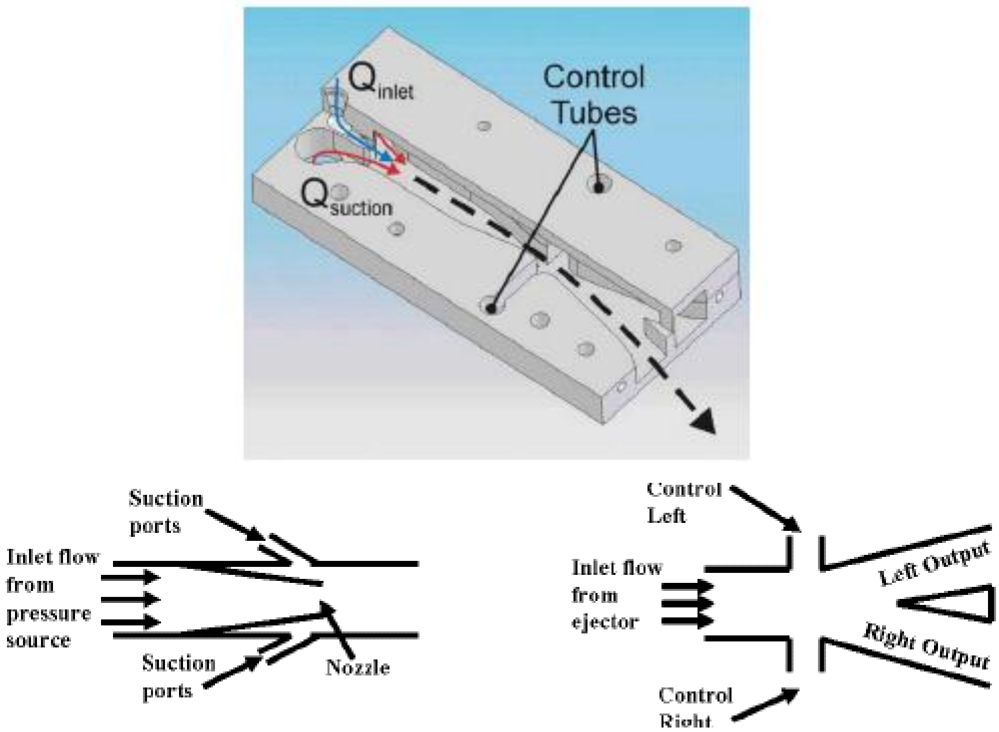

Figure 12: The suction and oscillatory actuator

Figure 12 shows the small size (overall length 60mm) suction and oscillatory blowing actuator along with schematic view of ejector and switching valve. Figure 13 depicts actual experimental set up.

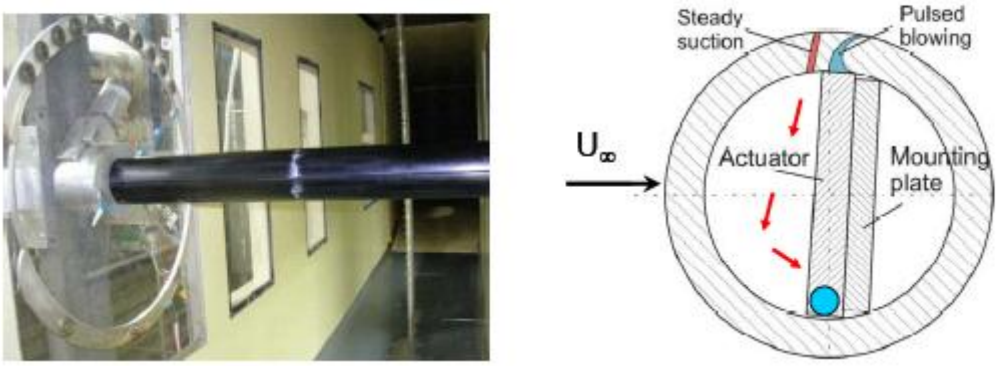

Figure 13: A sketch of the cylinder Setup (right) with the suction holes (red) and the tangential slot (light blue) installed at the Meadow-Knapp Wind Tunnel (left). An array of 15 SaOB actuators was installed in the cylinder. The sketch on the right also shows the mounting plate for synchronization and pressure supply (right, light blue circle). The arrows indicate the path of the suction flow.

Another novel AFC method used by M. El-Alti (2009) to reduce the vortex drag behind a trailer truck. Flaps are mounted at an angle which induces separation and synthetic jet actuators are placed close to the corner of the rear-end and the flaps. The computations propose an optimal flap angle of 30° to the free stream and C_μ of 1%. The gained drag reduction is of order 30%. The flow is analyzed by comparing the phase averaged and time-averaged flow field of the unforced and the forced cases. The full-scale prototype consist of a Volvo truck-trailer. The trailer has been mounted by three flaps at the rear-sides and top-end. The actuators consist of loud speakers in sealed cavities, connected to amplifiers which are supplied with a frequency generator controlled by LabVIEW. The full-scale test includes passive and active flow control investigations by varying the flap angle, with and without AFC, investigating different frequency and slot angle configurations. During the full-scale test the fuel flux is measured. The test show a fuel reduction of about 4% comparing two flap angles. The test of active flow control show a reduction of 5.3% compared to the corresponding unforced case.

Figure 14: The Volvo full scale test vehicle

The concept of moving surface boundary-layer control, as applied to a Joukowsky airfoil, is investigated by Modi and Yokomizo (1994) through a planned experimental programme complemented by numerical studies. The moving surface was provided by rotating cylinders located at the leading edge and/or trailing edge as well as top surface of the airfoil. Results suggest that the concept is quite promising, leading to a substantial increase in lift and a delay in stall. Depending on the performance desired, appropriate combinations of cylinder geometry, location and speed can be selected to obtain favourable results over a wide range of angle of attack. The experimental models are shown in Figure 15. Results show that injection of momentum through moving surfaces, achieved here by introduction of bearing-mounted, motor driven, hollow cylinders, can significantly delay separation of the boundary-layer and reduce the pressure drag. The momentum injection procedure also proved effective in arresting wind-induced vortex resonance and galloping type of instabilities.

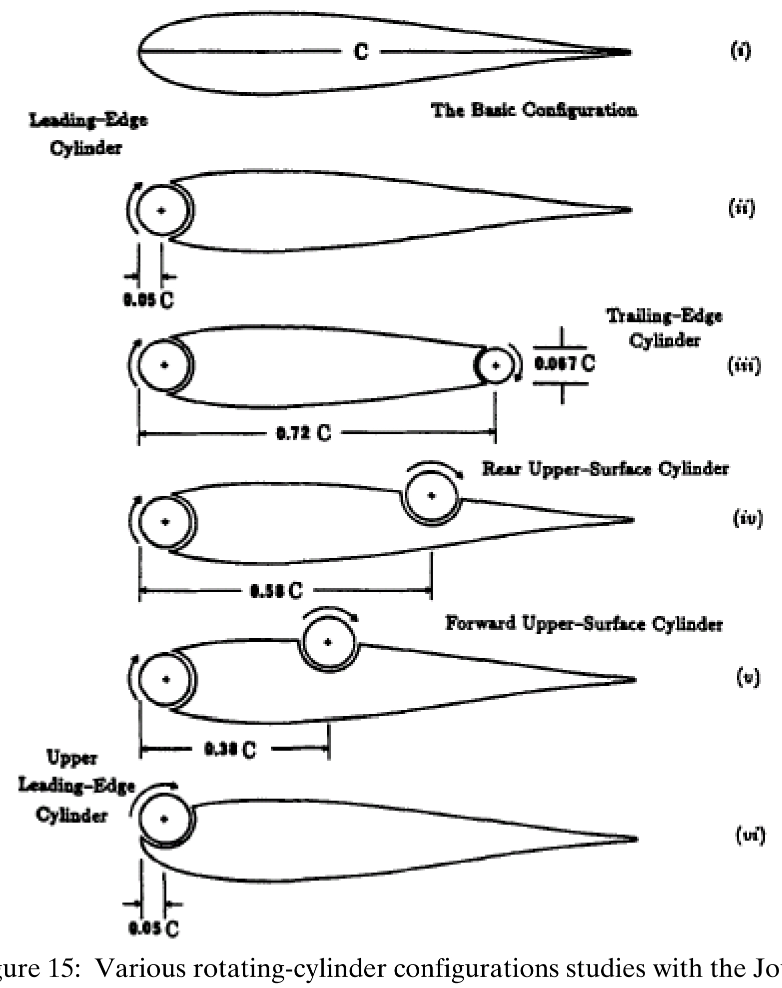

Figure 15: Various rotating-cylinder configurations studies with the Joukowsky airfoil model.

The effect of combination of two active control methods on drag reduction of a Ahmed body model is investigated by M. Abbaspour and M. Jahanmiri (2010). The air is sucked in order to delay separation at the beginning of rear slant surface and the same air is blown in to the wake region to increase the base pressure and so as to produce the thrust for the model. Ahmed model was selected for this research for its geometric simplicity. As expected, the suction leads to reduction of wake region and blowing resulted in slight base pressure recovery. The results show that by increasing the control mass flow rate, drag force decreases (see Figure 16a) . In addition, increasing blowing area with a constant mass flow rate leads to slight reduction in drag force. It is observed that about 30 percent drag reduction is achieved in the first case (blowing from the middle one third of rear vertical part) and in the second case (blow from the middle one half of rear vertical part) and changing the area of blowing section does not decrease drag coefficient. This research shows that the simultaneous use of suction and base blowing can lead to considerable reduction in drag force. However, the results depict that blowing has very small effect on drag reduction in comparison with applying only suction reported in other literatures. Experiments also carried out on same test configuration (Figure 16b) and confirms the computation data, the results of which appeared in Abbaspour (2010)..

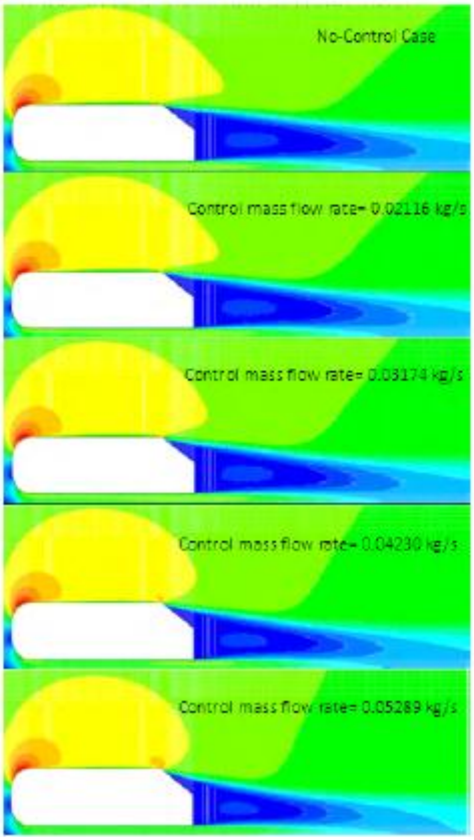

Figure 16a: Decrement of wake region by increasing control mass flow rate

Figure 16b: The experimental model, upper surface shows suction and lower surface is blowing area.

3. Propulsion Technology

Modern gas-turbine engines are complex systems that convert chemical potential energy into useful flow energy safely, reliably, and efficiently, with minimum life cycle cost and weight. As such, they move large quantities of air, and their ability to deliver depends on our ability to control that flow. The emerging field of flow control thus has the potential for significant impact on gas turbine engines. Below, some possibilities for application of flow control technology in gas turbine components are outlined.

One of the first flow control applications to receive considerable attention in gas turbine applications is active compressor stability control. If the compressor operated closer to the stall boundary, then additional work could be obtained per stage, and hence fewer stages would be required. The current approach avoids stall by scheduled bleed and stator vane actuation. This schedule is based on engine tests, and must therefore allow stall margin to account for engine to engine variability, wear (primarily tip clearances), thermal transients, and disturbances such as pressure or thermal distortion. This margin could be reduced if feedback were used; this requires some precursor to detect the imminent onset of stall. Furthermore, if one could use feedback to stabilize the unstable dynamics, one could potentially operate past the stall boundary, resulting in even greater work per stage. There are considerable references for this subject, see for example de Jager (1995) and the references therein. Actuation approaches include bleed (Eveker et al. 1998) and air injection near the blade tips (D' Andrea et al. 1997).

The Directed Synthetic Jet or DSJ, shown in Figure 17, is one possible separation control approach that may be appropriate for this application (McCormick 2000). The DSJ enables complete reattachment of the flow through boundary layer energization; both the instroke and the outstroke of the synthetic jet contribute to improving the boundary layer profile. Applying separation control to the intermediate case could enable more aggressive turning. This would allow either a shorter transition, or a higher offset, or some combination of these. This could be traded either for weight and length reduction of the intermediate case , or to keep the low pressure compressor aft flow path at higher radius for higher work and fewer stages.

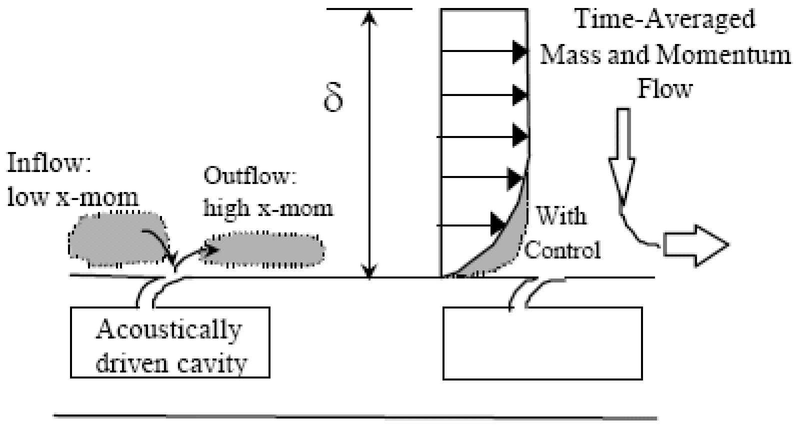

Figure 17: Directed Synthetic Jet for separation control. Instroke removes low momentum fluid; outstroke energizes boundary layer.

Active control methods have considerable potential in combustion. Experiments carried out on small and medium scale systems indicate that active control may be used to reorganize the flame region, improve mixing, modify the flame volume, or obtain a dynamic staging of the reaction zone. Open-loop control has already been employed to reduce nitric oxide emission levels. Further progress in this area will require a deeper understanding of flame interactions with external perturbations. In particular, it is necessary to develop basic studies on combustion/acoustic coupling and examine how modulations of air and fuel can be synchronized to attain optimal operation. Active control is also potentially useful in reducing instabilities that may appear in advanced systems like the lean premixed combustors which are now being developed for gas turbines and aircraft engines. While these systems produce low NOx levels, they are often unstable. Pressure oscillations which appear under unstable conditions may then lead to flashback or flame blow out. Active control might be -useful in preventing this unacceptable dynamical response and, in this sense, it might also help enhance the operation of the combustion system. Practical application of active control concepts is not straightforward. It will require further studies of basic mechanisms, examination of scaling problems, as well as more technological investigations focusing on sensors, actuators, and control algorithms. Reliability concerns in hostile environments will have to be treated carefully.

Flow control techniques for increasing the rate of jet mixing in axisymmetric nozzle flows have been investigated by Behrouzi et al. (2008). A combination of water tunnel and high-speed airflow facilities is used to assess the near-field jet behaviour. Solid tabs, steady fluid tabs (i.e. discrete radially discharged control jets located close to the core jet exit), and pulsed fluid tabs are compared. The effect of fluid tab velocity amplitude, pulse rate, and pulse phase are studied using open loop control. The measurements indicate that fluid tabs generate a similar streamwise vortex formation process (and hence display increased mixing) as previously observed in solid-tabbed nozzle flows. In incompressible testing the mixing effectiveness with a pair of pulsed fluid tabs180u out-of-phase was as good as a twin solid tab nozzle for a control jet flow rate of only 0.5 percent of the primary (core) jet flow. A sketch of the pulse generator unit is given in Figure 18. The rotating disc was located between end plates; single short inlet/exit pipes fed water to the unit from the pump, and distributed the water to the two fluid tab supply tubes in the nozzle. The mixing effectiveness achieved was shown to be optimized by a suitable choice of pulsation frequency and phase.

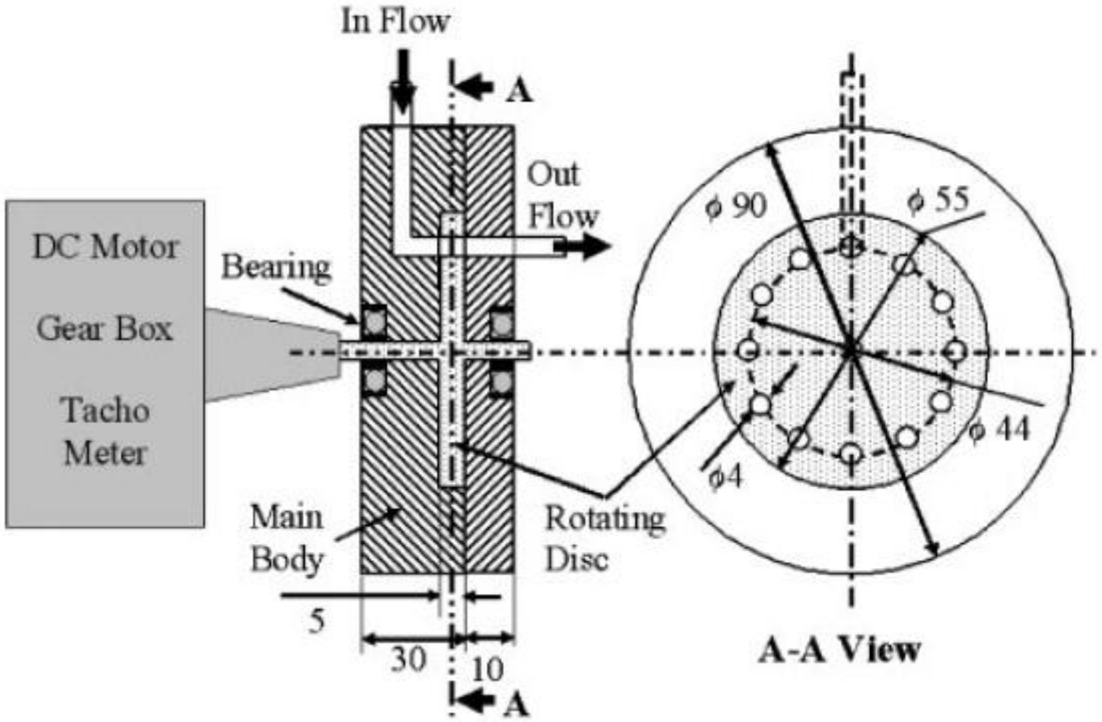

Figure 18: Rotating disc pulse generator unit

Flow control has the potential to make a significant impact on the turbofan engine. The ability to design the desired fluid dynamic behavior has always been the key to designing gas turbine engines. Flow control has the potential to be a breakthrough technology that enables a step change in our ability to design the fluid mechanics, and break fundamental barriers that limit performance. The review paper by Lord et al.(2000) gives some more detail on recent advances in flow control strategies in gas turbine engines. A more recent study by Horn et al.(2008) gives a roadmap for the development of smart systems and potential active control technologies for a more intelligent aircraft engine.

Concluding remarks

Successful implementation of active flow control requires an interdisciplinary approach, involving the classical disciplines of fluid mechanics, structural mechanics, material science, acoustics, systems, multidisciplinary optimization, and stability and control. Traditionally, technology development has occurred with researchers working in their own isolated fields of specialization. This trend has developed not only in universities, but also in government laboratories and industry. The recent trend has been to develop integrated, interdisciplinary, or multidisciplinary design teams to cross-fertilize and integrate component technologies. Coordinating research programs in which individual disciplines are supported in a collaborative environment will cultivate the development of breakthroughs in active flow control technologies. As the traditional fields are individually maturing, the integration of these disciplines holds exciting, uncharted new areas of research and technology development. The successful application of active flow control requires our willingness to not limit ourselves to one field of specialization, but to perform research and development in an interdisciplinary environment.

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