Flow Control and Diagnostics

FOREWORD

Flow diagnostics and control have always been of great importance in fluid-dynamical technology, but in recent decades they have become particularly active and exciting areas of research. In September 1998, IUTAM sponsored an international symposium on flow control at Göttingen (G E A Meier and P R Viswanath (eds) 1999 *Mechanics of Active and Passive Flow Control*, Kluwer). Since then the great surge of interest has continued, for several good reasons. The first is the potential for control of turbulent flows revealed by the discovery of coherent structures in what generally had earlier been considered as motion with complete disorder. A second reason is the related development of the theory of nonlinear dynamical systems. Such systems are sensitive to small changes in initial conditions, and therefore necessarily also to small control signals if applied at the right time and place. Third, great advances have recently been made in the technology of sensors, actuators, computers and related systems, making it feasible to consider small active control systems with a performance surpassing those that had earlier been available. Progress in MEMS and in nanotechnologies is unveiling ever newer possibilities. There is thus much interesting research being done in passive, active and hybrid methods of control; new experiments, computations and advances in the theory of control of continuous systems have all contributed to the excitement. And of course the potential benefits of turbulence management, to reduce or enhance drag, lift, heat transfer, mixing etc. as the application requires, are huge.

An Academy Discussion Meeting to consider these recent advances therefore seemed most appropriate. The meeting was organized in the pleasant environs of Orange County, Coorg, on 19–22 February 2006. There were 27 participants including several from USA and UK. The four-day programme included 22 presentations in sessions that dealt with flow control, flow diagnostics and flow instability. Of these, the texts of 13 papers presented at the meeting are now published in this issue.

The subject of the papers divides broadly into three areas: diagnostics (3 papers), stability (3 papers) and control (7 papers). The papers on stability are sandwiched between those in the other two areas, because an understanding of instabilities in the flow sought to be controlled has implications for both diagnostics and control.

We begin with an account of flow diagnostics using fibre optics by Vasudevan, Padbidri and Krishnan. A multi-component wind tunnel balance, working with fibre-optic sensors, was already demonstrated by the authors in 1999. They have further developed their techniques since then, and show how fibre-optic sensors have been effectively used for underwater applications and aerodynamic load measurements at hypersonic speeds. One advantage of fibre-optic sensors is illustrated by their ability to measure strain on a heated surface in a combustion chamber where the temperature could be as high as 1900°C. Furthermore, fibre-optic strain gauges are an order of magnitude smaller than the smallest resistive strain gauges available. The authors go on to describe measurements of normal and drag forces in the 300 mm diameter hypersonic tunnel at the Department of Aerospace Engineering, IISc, at a Mach number of 7, and in the 1 m × 1 m water tunnel at the Department of Mechanical

Engineering at IISc. Apart from these two applications they describe in detail, fibre-optic sensors are also being used to measure skin friction at low speeds and the drag on automobile models. The authors emphasize the many advantages of such sensor systems in terms of compactness and of their ability to acquire data under hostile thermal conditions.

In recent years, the technique of pressure-sensitive paints (PSP) is being used increasingly often for mapping surface pressure fields on wind tunnel models. The paint is a fluorescent material, which is excited when illuminated with light of appropriate wavelength. Once the emission from the PSP is imaged with a CCD camera, considerable data processing is required to derive the pressure field. In particular, image coordinates have to be mapped on the 3D model through a method called resection. The paper by Channa Raju and Venkatakrishnan describes a data-processing methodology and software, based on the resection approach developed at NAL during the last few years using principles of optical photogrammetry. Experiments on wing-body and delta wing models are described, and it is shown that the resection methodology developed by the authors has a higher resolution, especially when large gradients in pressure or significantly three-dimensional regions are involved.

The third paper by R Narasimha reviews the use of wavelet methods for detection of coherent structures in turbulent-flow imagery. Wavelets can be effective spatial filters on any image, and so are able to reveal the presence of order in imagery when such order cannot otherwise be easily detected. The use of the method is illustrated by applying it to the mixing layer, where the order is often visible in short-exposure photography, and in the jet where order is not easy to detect. It is emphasized that the methods can reveal the presence of a coherent structure even in a single image (i.e. no averaging is involved). Narasimha also describes recent work in which a wavelet movie at an appropriate scale can enable the life cycle of a coherent structure to be tracked. Such techniques (perhaps using discrete wavelet transforms) can be useful in processing data from an array of sensors in order to derive the signals that may be fed to an actuator in an active control system.

When a gas turbine engine operates close to its peak performance, flow within the compressor can become unstable. Handling such an instability is a challenge to engine designers. The instability may take the form of what is called surge, which can affect the whole turbine system. Surge is characterized by large-amplitude limit cycle oscillations in the mass flow rate and the pressure ratio. The root cause of surge is the loss of the pressurizing ability of the compressor. Viswanatha Rao and Ramesh describe a simple desk-top model of a compression system that can exhibit the essential features of surge, including the different types known as mild, classical and deep surge. By changing the volume of the plenum continuously they are able to measure its effect on surge frequencies, and map domains affected by classical and mild surges. They report that classical theories over-predict surge frequencies.

P K Sen and his coworkers present a stability theory for the organized structures found in wall turbulence. Using an extended Orr–Sommerfeld equation based on an anisotropic eddy viscosity model, they show that there is a wide range of unstable wall modes which mimic some of the key features of turbulent wall flows. The paper describes experiments whose results can be compared with the authors' theory. The experiments are conducted in a low-speed wind tunnel in which flow disturbances are excited by a loud speaker. The measurements are close to the predictions of the theory. The authors also analyse results from the extended Orr–Sommerfeld equation on compliant surfaces, and show that with a proper choice of wall parameters, unstable Tollmien–Schlichting modes can be completely eliminated on a compliant wall. Related work on Klebanoff modes and by-pass transition is also presented.

A Sameen and Rama Govindarajan review some of their work on the effect of wall heating on the stability of laminar flow in a channel. In the last twenty years the importance of transient growth in relation to transition to turbulent flow has been increasingly appreciated. The authors find from their comprehensive study of the effects of heat in channel flow that the most unstable linear mode is suppressed when viscosity decreases towards the wall. The transient growth of disturbances is unaffected by viscosity stratification but is enormously enhanced by reduced heat diffusivity. Both of these effects run counter to that on the least stable linear mode.

P R Viswanath presents a review of separation control strategies based on the extensive work he and his colleagues have done over several decades. Control of separation is a major objective in many technological applications, as flow separation generally increases energy loss and instability. Viswanath defines a separation control strategy as an '(intelligent) fluid dynamical plan which results in a desired alteration or modification of a separated flow'. He looks at three possible strategies: energization of the boundary layer upstream of the separation point, modifying the flow in the separation bubble, and direct or nearly direct manipulation of shear layer reattachment after separation. The first strategy has been the one traditionally used. The second has been in use for quite some time in such well-known methods as the use of suction downstream of separation or the insertion of splitter plates in a wake behind a bluff body for suppressing vortex shedding. The author demonstrates the third strategy through results of experiments involving tangential blowing downstream of separation but inside the bubble (D-type blowing), and the reduction of the intensity of surface pressure fluctuations in a transonic turbulent separated flow using a porous surface. He shows that with D-type blowing reattachment or wake closure can be eliminated, and in the porous surface experiments peak pressure fluctuations could be reduced by as much as 30%.

M S Chandrasekhara reports on experiments to control dynamic stall using a variable droop leading edge (VDLE) aerofoil. It is well known that considerable additional lift can be generated on an aerofoil past the static stall angle if the aerofoil can be rapidly pitched up and down. Such pitching is associated with dynamic stall and can be of benefit due to the additional circulation associated with leading-edge stall vortices. However, their uncontrolled convection over the aerofoil surface produces violent pitching moment fluctuations. A wing or a blade is usually prevented from entering dynamic stall to avoid its adverse effects, but as increasing demands are placed on new systems it has become worthwhile to see if lift can be enhanced beyond stall. Chandrasekhara explores the idea that convection of the leading-edge vortices can be managed through the pressure gradients, which in turn can be varied by shape adaptation. In the VDLE aerofoil which he studies the leading 25% of the aerofoil is maintained at zero incidence and the trailing 75% is oscillated with an amplitude of 10° around a mean angle of attack of 10°. Experimental results show that with the oscillation, even without the leading edge droop, the lift is augmented substantially when compared to the steady flow cases. In the VDLE mode the lift increment is slightly less but the pressure drag is reduced by about 50%.

Diwan and Ramesh examine the dynamics and control of laminar separation bubbles that are often present on the suction surface of an aerofoil at large angles of attack. Their approach is to study the response of the bubble to external excitations which are introduced through a loud speaker upstream of separation at the location of minimum pressure. They find that the response of the flow takes the form of a wave packet which is dispersed as it travels downstream. However, there are two regimes in the downstream development of the wave packet, as the velocity of propagation of the packet switches at a location slightly upstream of the maximum height of the bubble. At a higher excitation level the shape of the bubble is substantially altered and the disturbance levels in the bubble upstream of maximum height are enhanced.

Sharma and Pant report an experiment using pulsating surface blowing to control the vortex shedding from the blunt base of an aerofoil model. Their use of pulsed blowing introduces the frequency of pulsation as an additional parameter. They find that momentum injection in short spurts in one of the separated shear layers at the base is extremely effective in suppressing vortex shedding, depending on a combination of the strength and frequency of blowing.

The atmospheric flight of hypersonic vehicles causes severe heating especially at the front stagnation point, a problem which is usually addressed by using large-angle blunt-nose cones. However, such a configuration also increases the drag. There are many advantages in being able to reduce the drag experienced by the blunt nose. Kumar and Reddy show how drag can be reduced appreciably by using a counter-flowing supersonic jet emanating from the stagnation point of the blunt body. From tests made on a 60° apex angle model at the HST-2 shock tunnel at IISc at a Mach number of 8, they show that a drag reduction of about 25% can be achieved. Such aerodynamic methods are preferable to the use of forward-facing spikes which can become very hot, and may even ablate, due to aerodynamic heating at hypersonic Mach numbers.

Rajagopalan and Antonia review methods of modifying the structure of plane and circular jets and cylinder wakes using active, passive and hybrid techniques. For passive control, they study the effect of introducing a slender object such as a wire or ring, or a mesh, downstream of the nozzle exit plane. For active control they excite the flow either by acoustic speakers or by vibrating piezo-ceramic elements mounted around the nozzle periphery. They find that passive techniques generally lead to turbulence suppression, but can also be used to enhance turbulence if the potential core of the jet can be perturbed (e.g. by introducing a large cylinder). Active control strategies can yield turbulence suppression or enhancement, depending on the frequency of excitation. A hybrid technique that combines the features of both active and passive control is found to be very useful in suppressing large structures (comparable to nozzle diameter or width), which cannot otherwise be manipulated easily. In flow past cylinders, a small control cylinder upstream of the main cylinder can lead to a reduction in the total drag of the two bodies together compared to that of the main cylinder alone. They also document changes in the structure of the wake that are consistent with the observed reduction in drag.

Finally, Chakravarthy, Sivakumar and Shreenivasan examine applications of flow control in combustion. They study two simple geometries, namely the confined bluff body and the confined backward-facing step. Their data indicate regimes of flow acoustic lock-on that signifies onset of combustion instability and excitation of high amplitude discrete bands of sound in the combustor. High-speed chemo-luminescence imaging of the combustion area shows that the heat release rate fluctuates at the same frequencies as seen in the acoustic spectra. They conclude that under low Mach number conditions combustion processes can alter the underlying fluid dynamical processes appreciably.

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