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Introduction

Recent advances in technology for the fabrication, in bulk, of small sensors and actuators have enabled the use of these devices for flow control. It is probably true to say that our understanding of many aspects of fluid flow is sufficiently mature for there now to be ways in which it may be exploited for the technologically important area of active flow control. In this application, the use of MEMS (Micro-Electro-Mechanical Systems, or microstructures) is still in its infancy. Such devices are especially useful in turbulent flows found in engineering where much important information resides in ‘small’ eddies near surfaces. Similarly, the application of modern control theory to the distributed control of fluid flow has been exploited by only a few researchers in fluid mechanics. The design of a robust, distributed controller that is applicable to even a single specific flow-control problem is still some way off. Closed-loop control demonstration experiments are still lacking and there is a particular need for, and sharing of, proof-of-concept simulations and experiments.

The principal aim of the Symposium was to bring together many of the world’s experts in fluid mechanics, control theory and microfabrication to discover the synergy that can lead to real advances and perhaps find ways in which collaborative projects may proceed. Industrial participants could expect to have direct access to world-leading practitioners across these disciplines and to be brought right up to date with the latest developments. Correspondingly, academic workers could expect to be exposed to ‘real-world’ problems. One session was devoted to applications of open- and closed-loop control to problems in both internal and external aerodynamics. The purpose of this session is to identify potential solutions to industry-specific problems. A further session was devoted to presentations of results from the *2nd European Forum on Flow Control*, April–June 2006, held at the University of Poitiers.

The meeting attracted approximately 120 participants from UK (50), France (28), Germany (6), Italy (1), USA (20), Australia (3), Israel (2), Canada (1), Switzerland (1), Spain (1), Sweden (1), China & Hong Kong (3), India (1) and Korea (1). Of these, approximately 12 participants came from the aeronautical and automotive industries.

Ten keynote talks were given on a variety of topics stemming from active flow control experiments and simulations to fundamental design issues concerning MEMS. They were:

- Miki Amitay (RPI, USA) “Synthetic jets and their applications for fluid/thermal systems”.
- Thomas Bewley (UCSD, USA) “Multiscale retrograde identification, estimation and forecasting of chaotic nonlinear systems”.
- Kenneth Breuer (Brown University, USA) “Models for adaptive feedforward control of turbulence”.
- Haecheon Choi (Seoul National University, Korea), “Active and passive controls for form drag reduction”.
- Mike Gaster (Queen Mary, London, UK) “Active control of laminar boundary layers disturbances”.
- Mark Glauser (Syracuse University, USA) “Low-dimensional tools for closed-loop flow control in high Reynolds number turbulent flows”.
- Dan Henningson (KTH, Sweden) “Model reduction and control of a cavity-driven separated boundary layer”.
- John Kim (UCLA, USA) “Physics and control of turbulent boundary layers”.
- Philippe Pernod (IEMN-LEMAC, France), “MEMS for flow control: Technological facilities and MMMS alternatives”.
- Mark Spearing (University of Southampton, UK) “High power density MEMS: Materials and structures requirements”.

A total of 32 oral presentations were given, together with 28 poster presentations. This volume provides written papers of nearly all oral and poster presentations.

In consultation with the Scientific Committee, and more generally with the Symposium at large, responses to two questions were sought:

- *Achievements to date – where are we in effective flow control?*; and
- *What are the remaining most important challenges?*

Responses were grouped into five groupings: sensors, actuators, flow definition, drag reduction and separation control.

- Sensors. Only one paper was offered concerning wall sensors (wall shear). This is perhaps surprising given their importance. Thermal sensors for measuring wall shear stress remain popular, despite being nonlinear and the inherent limitations to frequency response set by heat loss to the substrate. By comparison, techniques for the measurement of wall pressure are at a better stage of development, sensors are more robust and nearly linear. Typically the rms wall pressure is 10–20 times the rms wall shear stress. Development is still required for both and some key questions arose, such as accuracy and noise. For example, with filtering, how much freedom does a robust controller offer?
- Actuators. Many achievements to date such as Zero-Net-Mass-Flux (ZNMF) jets are built on silicon (bimorph, piezoelectric, small deflection, high frequency) and the semi-conductor industry. There was a strong focus on ZNMF jets, but are these necessarily the best for all control problems? There are potentially many different other types of actuator, and many innovations in new materials (e.g. polymers, C nanotubes – with/without doping, composites). Pernod introduced Magneto-Mechanical Microsystems (MMMs): here there some issues regarding

instabilities and/or non-continuum effects. In summary, it seems that the fluids community needs a better appreciation of what is available, and there are outstanding issues regarding the provision of cost-effective MEMS with a quick turn around.

- Flow Definition. We have a good understanding on how to apply modern control theory to fluids mechanics, and linear control theory seems promising. Key questions are:

  1. what is the minimum information required for flow control – density and location of sensors?
  2. Merits of blackbox vs. ‘intelligent’ control?
  3. How should a cost function be best defined?
  4. Need for better model reduction: smaller state-space models (controllability, observability are key); incorporation of better, and/or distributions of, sensors/actuators.

- Drag Reduction. We understand the fluid mechanics fairly well – but largely at low Reynolds number (‘bottom-up’). It is not all clear that the fundamental processes at high Reynolds number are intrinsically the same (‘top-down’) – what are the implications for flow control? Bewley stressed the importance of overlapping/decentralised controllers (fast$\sim$local, slow$\sim$non-local) and practical problems require issues of realizability to be addressed.
- Separation Control. This is probably the goal that is closest to application in a real system. Different types of actuator (or even variations on the same basic design) may all achieve separation delay even though the actuator may induce different flow physics. This may enable a more straightforward design (fewer parameters) and permit a greater emphasis on other considerations (e.g. robustness). For closed-loop control, optimum design requires coupled actuator-algorithm design from the start: e.g. shear-layer response time depends on actuator speed.

In terms of applications, much of the focus and investment is on the aeronautical sector, while, in fact, both marine and automotive sectors offer vast energy savings. John Kim pointed out that worldwide ocean shipping consumes 2.1 million barrels of oil *per annum* whereas the airline industry only uses 1.5 million. It is therefore somewhat ironic that several effective methods are known for reducing skin-friction drag in water flows but few work in air. However, it suggests that more investment should be targeted towards drag reduction of ships and road vehicles.

However, the ACARE 2020 targets have largely been adopted by the European airline industry. The challenge of achieving 50% reduction in fuel burn implies a wing/fuselage drag reduction of about 20%, an improvement in engine efficiency of about 20%, with the remainder coming from improved traffic management. In theory, arrays of microjets, dimples, pimples or other actuators combined with suitable sensors and control systems could produce substantial reductions in drag. Whether this is possible or not remains an open question. An estimate for the number of sublayer streaks present at any one time on the fuselage of an Airbus A340-300 in cruise is 10^9, and shows the scale of the problem for active control. Clearly, advances in the application of model reduction techniques to wall turbulence are an essential prerequisite before any sophisticated control technique involving cost functions and adjoint equations can be used. Fundamental differences between the behaviour of boundary layers at operational Reynolds numbers and the low Reynolds numbers at which control schemes have showed some success have yet to be addressed.

It is likely that only open-loop methods for turbulent skin-friction reduction that do not require a control system are likely to be feasible for practical application by 2020. The only such methods currently known are spanwise oscillations, randomized roughness and riblets.

It is clear that the industry/academe divide remains: the horizons needed by the aeronautical industries are far too short for what is expected. However, in Europe, environmental issues constitute a significant driver for research funding. But there is a need to encourage mechanisms for discipline crossover/hopping. Moreover, the fluids community needs to engage with MEMS and control people.

Jonathan Morrison
Jean-Paul Bonnet

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