Flow-control approaches to drag reduction in aerodynamics: progress and prospects

Flow control—the control of turbulence and turbulent flows, in particular—may be likened to the exercise of cupping water between two arthritic hands: frustratingly difficult and, at best, only partially successful. Harder still, innovative control concepts that are eventually brought to fruition in a laboratory setting face the additional, often major, obstacle of being translated into practical systems that operate effectively, efficiently and reliably over a wide range of conditions. Closing this gap is conditional on an ambitious collaboration—a meeting of minds—between university-based scientists and engineers in industry, with each group recognizing and responding creatively to the priorities and constraints of the other.

Most flow-control challenges arise simply from the fact that the stability characteristics of fluid flows—for example, those governing transition—are very difficult to influence using energy-efficient, fast-response sensor–actuator systems. Moreover, the highly complex, multi-scale nature of turbulence makes it very hard to target particular mechanisms with actuation devices that, necessarily, operate within a narrow range of scales, or even a single scale. An example in the latter area is the reduction of frictional drag, requiring control over both the small-scale streaky structure in the viscosity-affected near-wall layer and the large-scale structures (‘super-streaks’) in the outer, fully turbulent region—and this needs to be achieved using only a small number of fixed wall-mounted sensors and actuators.

The principal driver of flow control is the pressure to reduce fuel consumption and hence CO₂ emissions, especially in civil aviation, but also in road and shipping transport, which together are responsible for around 30 per cent of global CO₂ emissions. Global aviation-fuel consumption alone is estimated to rise from 155 million tonnes in 2002 to almost 400 million tonnes in 2030 [1,2], with consequent CO₂ emissions rising to 1250 million tonnes. A 1 per cent reduction in drag on a jet airliner in cruise conditions translates roughly to a 0.75 per cent reduction in fuel consumption, implying a potential reduction in emitted CO₂ of nine million tonnes per 1 per cent of drag reduction. In the case of a modern airliner, friction (viscous) drag amounts to about 60 per cent of the total drag, the remainder being mostly shape, induced and trim...
drag [3]. Hence, viscous drag (followed by form drag) remains the area of largest potential for drag reduction that will most readily translate to significant fuel and CO₂ reductions.

Engineering-imposed constraints have, so far, inhibited the practical exploitation of advanced laboratory concepts and techniques in active flow control. As is exemplified by the last paper in this Theme Issue, by Spalart and McLean of Boeing Commercial Airplanes, even the most progressive aeronautical industries continue to favour very traditional, safe and simple, passive control by use of riblets for drag reduction and vortex generators for separation control. Open-loop suction, to delay transition, is probably the only active control method close to practical exploitation [3], but even this technique is inhibited by its demand for porous walls, subsurface plumbing and a mass-transport system.

The highly demanding EU targets that civil aviation has to meet in respect of CO₂ emissions—a reduction of 50 per cent by 2020 relative to the 2000 level [4]—dictate the pursuit of all, even vaguely promising, drag-reduction strategies, though their practical realizability may be unclear at the early stages of their exploration. Thus, industrial caution has not deterred university researchers from pursuing ever more ambitious developments of established flow-control methods as well as exploring novel concepts. A major proportion of recent and current efforts is covered by papers contained in the present Theme Issue.

Leaving aside fundamental explorations, to be noted later, research on specific control strategies covered herein falls broadly into three categories:

— the delay of transition, both passively using roughness elements, and by way of closed-loop systems that involve sensing instabilities and applying appropriately delayed counter-measures by means of plasma-, sound- or piezo-driven actuators;

— the reduction of near-wall turbulence by means of open-loop oscillatory or travelling-wave motion induced by wall movement and plasma actuation;

— the suppression of separation and control of vortex shedding from semi-infinite walls and aerofoils, with both open-loop and closed-loop control by means of pulsed or synthetic-jet actuators—and, associated with it, the control of circulation over aerofoils and bluff bodies.

Further papers covering more fundamental issues focus, *inter alia*, on: basic mechanisms of drag reduction by riblets; the applicability of linear-system analysis of skin-friction drag in boundary layers and related optimal control of drag reduction; and the stabilization of wake flows with reduced-order closed-loop schemes.

Taken together, this compendium of papers arguably provides a valuable state-of-the-art exposé that should be of interest to both academic researchers and industrial practitioners interested in the long-term potential of advanced concepts in flow control. The Editors hope that the issue will encourage a more vigorous debate on how to bridge the gap between academic research and industrial exploitation, with the objective of flow-control research making a tangible contribution to the environmental challenges that mankind faces.
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