5 Multiscale Active Flow Control

Pierre C. Perrier

Dassault Aviation, 92210 Saint-Cloud Cedex, France

Abstract. The physics of the multiscale patterns of flows is introduced in the first part: it is the foundation for analysis of the control of flow. Then a careful distinction is made between control as a passive mean for improving the properties of natural flows relevant to a given application, and control as a robust active tool to optimize a cost function. Improvements of the performances of engineering systems relying on flow of fluids may use passive means or active controller, sensors and actuators to withstand the external perturbations. Consideration of such types of active and passive control and of calming or increasing unsteadiness forms the subject matter of the following parts in flows of high Reynolds number relevant to major applications with turbulence or chaotic behavior. These progress towards increasing complexity of control: from the simpler control of amplitude of turbulence and chaos everywhere in the flow to achieve its homogenization to the more complex control aimed to reduce such amplitude. Methodology relying on a mix of experimental and numerical assessment of the problems and of possible solutions is needed for mastering the level of difficulties involved in complex flow control. The final part is devoted to the problems of applications, when a real-life controlled flow system is to be built, demonstrated and certified at the level of safety presently required for advanced aviation systems in operation.

1 Physics and its Modeling

1.1 Physics of Multiscale Flows

Sensitiveness. Underestimation of flow complexity is common in the field of fluid mechanics, both in applications and often in research. So much flow visualization at low Reynolds number and of computation with increased viscosity, by artificial dissipation of the numerical schemes, are now widespread, and have become the basis of physical knowledge of flows for many people. Both types of visualization succeed too much in extracting quasi-steady flow patterns, often the more attractive for researchers or engineers willing to consider simple explanations of mean properties of flows. Turning to a problem of active control implies that transient effects and their stability become of main importance in the study of control, and that the hypothesis of smooth mean flow properties is no longer relevant. Another error is to consider the behavior of the flow as a linear output of an excitation by actuators, and so assume that relevant unsteadiness is linear sum of forced outputs by the intended movements of actuators. Such framework of analysis of flows comes from the linear theory of the control of systems and is strictly valid only

© Springer-Verlag Berlin Heidelberg 1998
for linear systems. This is clearly what the flow of fluid is not, both when the Reynolds number is low because dissipation effects are predominant, and when the Reynolds number is large. Turbulent dissipation are then large particularly also in transitional regime because the transition process is highly nonlinear. Such remarks do not preclude the usefulness nor the efficiency of some basically linear controllers. However, in cases of failure of control at the design point, with large external perturbations, it reminds us that no useful analysis can be conducted from the linear viewpoint.

One basic characteristic of flows seen in practice at high Reynolds number is the capacity for a small perturbation to be convected and amplified on a space-time frame to many orders of magnitude larger than the initial perturbations entering the domain. Typically a small perturbation of $O(10^{-6})$ compared to mean external velocity and $O(10^{-3})$ compared to a characteristic length of the flow (width of a duct, wake, shear or boundary layer thickness) can fill all the domain with a perturbation $O(1)$. Such a process is therefore of major concern in the efficiency of any control aiming to reduce perturbations as far as very local control is not used (i.e. control reduced to the vicinity of the perturbation). The feeding of the unsteadiness of the flow by the actuators, designed for calming it, is a common output of linear control outside of its limited range of linear effect. Another parasitic effect is the transfer from one frequency (wavenumber) to another frequency (larger and smaller wave numbers) of the perturbation due to the nonlinear coupling of modes.

Major part of our knowledge in the field of control have been developed from the stability analysis of systems with reduced number of degrees of freedom or with clear separation of modes. It is usual in mechanical systems where a small number of eigen values keeps significant percentage of the energy stored from an impulsive solicitation. On the side of fluids such simplicity does not exist because the modes are not at fixed frequency regardless the fact that they may be seen (when a more amplified frequency lets a particular mode to appear) with more amplitude on some modes than on others. Mode frequency and possibly its shape will generally change downstream from the point of observation. So, the energy embedded in a given perturbation can be transfered to other frequencies, can be convected by mean flow or may have a significant relative traveling velocity, may eventually feed other modes. Such that the spreading of an initial perturbation is generally larger than anticipated from simple one-mode-convected linear analysis. One could consider as a challenge the control of flow patterns having such highly nonlinear behavior, but in fact it is the contrary. It means that the system constituted of the areas of interest is highly responsive to perturbations and so will be controlled with small inputs, if such inputs are adjusted to the possible self amplification where they are more sensitive. We need to turn to a sensitivity analysis of the flowfield at least for the flow irregularities of interest for the goal of control (see Lions, 1996).