4 Large-Scale-Structure Identification and Control in Turbulent Shear Flows

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Abstract. The control of turbulent shear flows can be achieved through the control of the large-scale structures. Indeed, even in fully turbulent shear flows, these large-scale structures are known to be of primary importance for most of the flow characteristics. Due to the turbulent character of flows under practical and industrial interests, the detection, analysis, prediction and control of the large-scale structures are quite complex. We present, in this chapter, several tools available for accessing these large-scale structures. Non conditional, stochastic methods, based on correlations, are preferentially detailed. In particular, the Proper Orthogonal Decomposition and the Linear Stochastic Estimation are described. As an illustration of the potentialities of these objective stochastic approaches, the particular case of the turbulent plane mixing layer is derived as a guide-line all along this chapter. In its last part this chapter will focus onto the way by which, using POD, low dimensional models of the structures can be derived, in the framework of a closed loop control of these structures. This approach, deeply related to the notion of deterministic chaos, is then emphasized. The important problem of the closure (mean flow/turbulent flow) appearing in this context is recalled. The last part of this chapter is devoted to a point that is specific and of importance for these stochastic approaches. The limits for the representation of the flow by these models when the flow configuration evolves have to be given. The methods able to take into account this evolution are of crucial importance and under rapid development.

1 Introduction

Industrial, applied and fundamental researchers alike are now convinced that large-scale, organized motions exist and play a crucial role in turbulent flows. These large-scale structures are known to have a recurrent character and most of the time they are quasi-periodic: at a given spatial location, they possess a preferential size and appear with a preferential frequency. Indeed, these characteristics are smeared by the turbulent nature of the flow and, unless artificially excited, possess a random distribution in size, location, frequency etc. Large-scale structure can then only be defined in a statistical way or by using specific concepts that will be described later in this chapter.

For example, in the case of a plane mixing layer, the preferred large-scale structure size is of the order of the vorticity thickness \( \delta_\omega \) with a typical frequency \( f_p \) corresponding to a Strouhal number \( S_\omega = f_p \delta_\omega / U_m \) of the order of 0.3 (see Chap. 6 of this book).
It has become increasingly evident that large-scale structures influence mixing, noise, vibrations, heat transfer, drag, lift etc. Therefore, understanding their morphology, their dynamics and how they interact with the surrounding fluid is often essential for the purpose of controlling turbulent flows.

As is the case for any type of flow control, large-scale structure control can be achieved by passive as well as by active means (for a review, see Chap. 1 of this book). However, regardless of which particular method is used to control the large-scale structures, it is first necessary to be able to identify them. In this first stage of flow control, experimentalists and numerical analysts are faced with two initial tasks which are to find out: 1) how to separate (extract) these structures from the background turbulence and 2) how their average characteristics (in terms of their more probable or dominant role) can be determined. These tasks are always complex and non-trivial because the large-scale structures are embedded in random fields and the technique used to determine when and where certain structures are passing or present is directly related to the definition of the coherent structures.

Section 2 will be devoted to this problem of large-scale structure identification. An overview of different methods will be discussed herein. A variety of detection or analysis methods (both multi- and single-point) are now available or are in various stages of development. The following is a list of the main methods that will be discussed: Topological Concept-based methods; Full Field Methods (e.g., pseudo flow visualization); Conditional Sampling (Vorticity-based and other methods); Wavelets; Pattern Recognition Analysis; Proper Orthogonal Decomposition; Stochastic Estimation. Detailed descriptions of these methods can be found in several reference papers (see for example (Adrian 1975), (Antonia 1981), (Glauser and George 1992), (Lesieur 1993), (Berkooz et al. 1993), (Schoppa and Hussain 1994)). The existence of numerous different methods can be surprising at first. This is related to the diversity of the nature of the data that are available from experiments and/or computations. The information available from experiments can be local (probes) or global (visualizations), time resolved (e.g. hot-wire anemometry) or randomly acquired, alternatively triggered by some event (e.g. laser Doppler velocimetry, visualization-based velocimetry). In general, the information available from experiments is poorly resolved in both time and space, and special efforts have to be made to address the global, large-scale character of the flow. This is particularly true when, as for most cases of practical interest, the flows are turbulent, three-dimensional and occur at high Reynolds numbers. On the other hand, and somewhat conversely, the information available from numerical simulations is quite complete, and is sufficiently resolved in both time and space, as in the case of Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES) for example. However, in these cases, the amount of information may be considered too large to be handled easily and to be interpreted in terms of large-scale structure. Therefore, for numerical simulations, it is generally necessary to choose properly