DRAG REDUCTION

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Flow control is strongly associated with drag reductions. Although there are a number of objectives for flow control, such as flow mixing, noise reduction and combustion control, drag reduction is often considered as a main motivation for flow control. In this lecture, we shall discuss the objectives and classification of drag reduction as an introduction to this topic, followed by a brief discussion of turbulent boundary layer structures. The drag reduction methodology will then be explained in terms of the modification of turbulence structures. The final section is devoted to recent developments in active turbulence control for drag reduction.

1. Objectives of drag reduction

By reducing drag force through flow control, one can achieve one or a combination of the followings:

- Improve fuel economy
- Increase vehicle speed
- Increase flight range
- Increase capacity
- Reduce flow noise

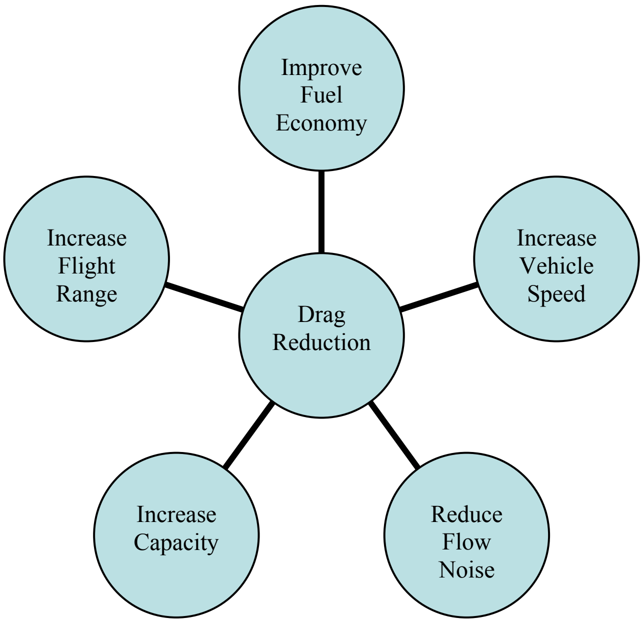

Figure 1. Objectives of drag reduction.

By carrying out drag reduction, airlines can, for example, not only reduce their operational cost by improving the fuel efficiency, but also increase the aircraft speed, flight range and capacity. They can therefore reduce the flight time and increase the number of direct flights as well as to increase the number of passengers or increase the cargo capacity. Flow noise is often associated with the turbulence level, which can also be reduced as a result of drag reduction.

2. Classification of drag reduction

Active control can produce a greater amount of drag reduction but with an expense of energy input for driving actuators, which can be quite costly. For example, turbulent skin-friction drag reduction could be up to 45% by spanwise wall oscillation technique, but the net reduction may be only about 15% if we consider the energy spent to move the wall surface (Baron and Quadrio 1996). On the other hand, the passive techniques such as riblets could give up to 10% without an expense of energy (Walsh 1982). There are other costs involved in passive drag reduction techniques, however, such as the cost of material, application and maintenance. Also the net drag reduction is not always the critical factor in choosing the technique. Control parameters should be carefully chosen so that the effects on the turbulent structures can be maximized. Usually the time, velocity and length scales of actuators are of similar order to the turbulence scales, which change with the Reynolds number.

Drag reduction can be performed in different ways, including:

- **Active** and passive technique
- **Open-loop** and closed-loop control
- **Turbulent** and laminar flow
- **Skin-friction drag**, pressure drag and induced drag
- **Air**, water and electrically conductive media
- **Experimental** and numerical method

The main focus of this lecture is active, open-loop control for a reduction of turbulent skin-friction drag in air using experimental techniques. Discussion on other flow control techniques can be found elsewhere (see, for example, Bad-el-Hak 2000).

3. Structure of turbulent wall flows

Nearly 80% of energy production in the turbulent boundary layers takes place during the turbulence activities/events (Lu and Willmarth 1973), such as sweeps and ejections, although there is still much debate on the essential structures of turbulent boundary layers (Robinson, 1991). It is, therefore, important to understand the structure of turbulent wall flows for effective drag reduction strategies.

The turbulent boundary layer structures are essentially consisting of hairpin vortices of different size which are distributed in time and space (Head and Bandyopadhyay 1981; Adrian 2007). Here, the hairpin vortices are attached to the wall, so that their legs are elongated into the flow direction (quasi-streamwise vortices). The sweep events that are associated with the downwash of high-speed flow (Q4 events with +u and –v velocity fluctuations) can be found on the downwash side of the hairpin legs, while the ejection events (Q2 events with –u and +v velocity fluctuations) are found on the upwash side of the legs (Willmarth and Lu 1972). Low-speed streaks are often observed during the flow visualisation in the viscous sublayer (Kline, Reynolds, Schraub and Runstadler 1967), where the low speed region can be pumped up along the legs of hairpin vortices. Hairpin legs can be observed either singly or in pairs, although they are formed in pairs.