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Active control of turbulent separated flows over slanted surfaces

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Abstract

The experimental investigations in the present paper deal with the excitation of fundamental instability mechanisms in separated free shear layers on a bluff body and downstream of a diffuser by means of periodic forcing in order to reduce the expansion of flow separation. The experiments focus on a unique approach to separation control using fundamental frequencies for local forcing in two different shear layer configurations (inner and outer diffusers). Each separation process is characterized by the periodic occurrence of large spanwise vortex structures. These vortices scale with the difference in height between the ramp ends. The excitation of these large scale vortex structures by periodic forcing intensifies the momentum transfer between the separation region and the outer flow, resulting in a substantial reduction of the reattachment length. For the inner and outer diffuser configurations, a universal value for the optimum forcing frequency was established.

Keywords: Active separation control; Bluff bodies; Channel flows; Vortex-shedding; Particle image velocimetry

1. Introduction

Flow separation from solid surfaces occurs in a variety of technical applications, such as expanding flow channels (diffusers) or car and train tails, in turbomachinery, on airfoils at high angles of attack etc. This inevitably leads to a significant decrease in efficiency (e.g., Hucho, 2002; Leder, 1992). Both active and passive methods of flow control can be applied to avoid or reduce this type of separation-induced performance loss (Lin et al., 1990; Yoshioka et al., 1999; Brunn and Nitsche, 2002 etc.) Nevertheless, practical applications are almost too complicated for an accurate analysis of these typical phenomena. Hence, generic models with the most important boundary conditions are frequently used.

An overcritical diffuser is the simplest geometry for studying flow separation phenomena. The separation process is characterized by the periodic occurrence of vortex structures. Fig. 1 shows the development of these structures in principle (Brunn, 2003): The initial Kelvin–Helmholtz-Instability (KHI) leads to a roll-up of small spanwise vortices caused by low pressure and vorticity fluctuations. These structures grow rapidly and are finally shedded from the separation region (vortex-shedding). The pressure fluctuations resulting from the shedding process propagate upstream and are reabsorbed close to the separation point, generating vorticity fluctuations, which enhance the shear layer roll-up (Kiya et al., 1997).

Investigations on active separation control in plane and axisymmetric diffusers (e.g., Brunn and Nitsche, 2002) or on simple bluff body geometries (Sigurdson, 1995; Kiya et al., 1997 etc.) were conducted successfully using forcing frequencies in the range of the observed shear layer instabilities. In these experiments wall embedded actuators were used to generate periodical perturbations, which significantly reduce the separation length.

Nevertheless, the more complicated the configuration is, the more complicated the flow structures become. This is

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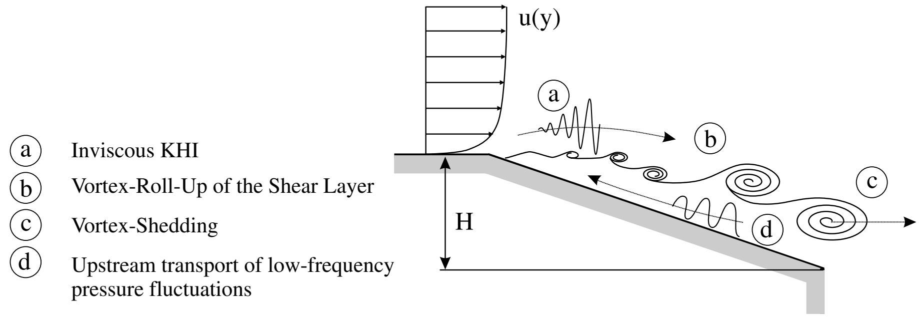

Fig. 1. Feedback-mechanism of instabilities in a separated shear layer (Brunn, 2003).

demonstrated, for instance, by Brunn (2003) in the transition from plane diffusors to axisymmetric configurations. Here the spanwise vortex structures, which have been shed from the separation region, lose their initial two-dimensional character in their early stages of development. It follows that the practicability of the proven control methods in complex geometries and real-flow applications has to be investigated.

The present experimental study focusses on the comparison of active separation control methods at a plane half diffuser and the flow behind a generic car model – the Ahmed Car Model (ACM, Ahmed et al., 1984). The flow control on this car model is an interesting application with respect to an increased efficiency of vehicles. The pressure drag is the major component of the total drag of a vehicle due to the flow separation at the rear end (Morel, 1978; Hucho, 2002). Consequently, a reduction of separation will result in a strongly decreased total drag. The ACM combines the essential geometrical parameters determining shape, length and position of the separation and is used as a reference for numerical and experimental investigations (e.g., Krajnovic and Davidson, 2002).

The study in hand uses the simple half diffuser configuration to demonstrate the receptivity of actuator perturbations in a quasi-two-dimensional separated shear layer in terms of frequency spectra of velocity fluctuations measured with a hot wire probe. In the second part of the study, the results of the first attempts of plane diffuser control are applied to a second, more complicated configuration to reduce the separation length behind a two-dimensional ACM and the connected total drag.

2. Experimental

The experimental investigations were conducted in two different flow channels: an open wind tunnel with a plane half diffuser as a test section for hot wire measurements in the separated shear layer to obtain fluctuation data in the time and frequency domain and a closed water channel in order to detect flow structures behind the generic car model (Ahmed-Body, Ahmed et al., 1984).

The half diffuser has an aspect ratio $AR = 10$ and a slant height of $H = 40$ mm, with the slant angle set at $\alpha = 25°$. The measurements were carried out at a Reynolds number based on the inflow velocity of $Re_H = 4 \times 10^4$. To reach a fully developed turbulent inlet flow, a tripping wire was placed at $100 \cdot H$ upstream the slant edge, fixing the laminar-turbulent transition far upstream. A loudspeaker-slit-actuator, situated directly at the slant edge of the diffuser, was used to generate sinusoidal pressure perturbations, and it was inclined at 45° to the mean flow direction based on the investigations of Lin et al. (1990); Yoshioka et al. (1999); Brunn (2003). A single hot wire probe was traversed in the symmetrical plane of the flow field to measure the velocity fluctuations (Fig. 2). The complete set-up is documented in the study by Brunn (2003).

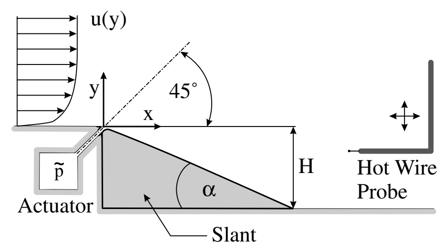

Fig. 2. Cross-section of the plane half diffuser with actuator and the hot wire probe.

The measurements at the ACM were conducted in an optically fully accessible water test section using particle image velocimetry (PIV) and digital flow visualization methods. The PIV-system consists of a frequency-doubled Nd:YAG laser, two CCD-cross-correlation-cameras to observe the near and the far wake region simultaneously and a synchronization unit (Fig. 3).

The ACM, which stretched across the whole width of the test section ($AR = B/H \approx 8$), was mounted on the channel wall with a ground clearance of $0.39 \cdot H$. The slant angle was set at $\alpha = 35°$, because observations on the fully three-dimensional model by e.g. Ahmed et al. (1984); Lienhart et al. (2002) show that the flow field of the slant region is dominated by two-dimensional spanwise vortex structures under these conditions. The initial three-dimensional flow structures at the rear side edges of the ACM should be largely suppressed through the two-dimensional stretching. All other geometrical parameters of the model are based on the original data given by Ahmed et al. (1984). The Reynolds number based on the inflow velocity and the slant