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Experiments on the turbulent wake of a flat plate in a strong adverse pressure gradient

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Abstract

The wake of a flat plate was subjected to an adverse pressure gradient of sufficient strength to cause local mean-flow reversal. The mean-flow and turbulence statistics were determined with a three-component laser Doppler anemometer. The experimental data were used to determine balances of the momentum equation and the turbulence kinetic-energy equation. The latter showed that the production of turbulence kinetic energy remained at a constant high level whereas the dissipation decreased when moving past the trailing edge into the wake. As a consequence, the turbulence kinetic energy becomes very high in the wake. Spectral density functions measured at various locations in the wake indicate that turbulence kinetic energy accumulates in the very low-frequency range. It is suggested that this is due to the formation of unsteady roll cells in the trailing-edge region.

Keywords: High-lift aerodynamics; Turbulent wake; Adverse pressure gradient

1. Introduction

This investigation of an adverse pressure-gradient wake is related to one particular feature of high-lift aerodynamics, i.e. the development of the wake of the main element in the pressure field that is induced by the flap. An accurate numerical prediction of the near wake of the main element is highly desirable because it has a significant effect on the lift, especially at high incidence. However, as was shown by Adair and Horne (1989) and Nakayama et al. (1990), this wake is extremely complex owing to the combined effects of curvature, asymmetry, streamwise pressure gradients and the interaction between the wake and the boundary layer on the flap. In a most interesting series of wind-tunnel tests on a multi-element airfoil, Petrov (1980) showed that the wake of the main element can exhibit a region with mean-flow reversal that is detached from the surfaces of the various elements (see Fig. 1). Petrov called this phenomenon "detached separation," because the backflow region is separated from the surfaces of the elements by a relatively thin zone that consists of an attached boundary layer and a region of potential flow. Perhaps "free separation" or "off-body separation" is a better label, because "detachment" usually refers to the location in a separating turbulent boundary layer where the wall-shear stress vanishes (Simpson et al., 1981).

The free-separation phenomenon is interesting since it does not occur in flows about single-element airfoils where separation takes place on the surface of the airfoil. The stall of a multi-element airfoil is not always caused by boundary-layer separation on the flap or the aft portion of the main element. The stall can also occur when a zone of reversed flow in the wake of the main airfoil rapidly widens and propagates upstream. In fact, due to the thickening of this main-airfoil wake, the boundary-layer separation on the flap, which occurred at moderate angles of attack in Petrov's experiment, disappeared with increasing incidence.

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Nomenclature

a_{sp}	structural parameter ($=\overline{u'v'_s}/k$)
C_f	skin-friction coefficient ($=2\tau_w/(\rho U_e^2)$)
C_p	static-pressure coefficient
H	shape factor ($=\delta^*/\theta$)
k	turbulence kinetic energy
n	coordinate normal to plate surface
P_k	production of turbulence kinetic energy
$\overline{p}_m$	measured static pressure
R_θ	Reynolds number based on momentum thickness
r	radius of curvature
s	coordinate along surface of flat plate
U_e	velocity at edge of shear layer
U_{ref}	free stream velocity
$\overline{u'v'}$	Reynolds shear stress
$\overline{u'v'_s}$	Reynolds shear stress in streamline coordinates
$\overline{u'^2}$	Reynolds normal stress for x-direction
$\overline{v'^2}$	Reynolds normal stress for y-direction
x	coordinate along wind-tunnel axis
y	lateral coordinate
δ^*	displacement thickness
ϵ	dissipation rate
θ	momentum thickness
κ	Von Karman constant
ν	kinematic viscosity
τ_w	wall-shear stress
ω	radial frequency

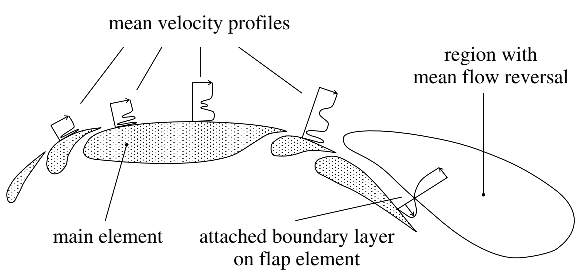

Fig. 1. Illustration of free-separation in the flow around a multi-element airfoil as observed by Petrov (1980).

Consequently, the flow on the flap and on the main element remained fully attached during the stall. This was also reported by, for example, Johnston and Horton (1986).

There are only a few investigations of the free-separation phenomenon, despite its practical significance in high-lift aerodynamics or other technical applications in which free shear layers are subjected to severe streamwise pressure gradients. Over the past decade the phenomenon has attracted some attention as evidenced by the work of Liu et al. (2002), Driver and Mateer (2002), Hoffenberg and Sullivan (1998) and Tummers et al. (1997). An interesting early contribution is the experiment performed by Hill et al. (1963), who investigated the effects of streamwise pressure gradients on the decay of wakes. They subjected the wake of a thick plate with a streamlined nose to adverse pressure gradients of various strengths by means of a diffusing wind-tunnel section with variable side walls. The experiments of Hill et al. (1963) showed that the maximum velocity defect in an adverse pressure-gradient wake decreases at a slower rate than in the constant-pressure wake of the same body. For a sufficiently strong pressure gradient, the maximum velocity defect increased rather than decreased, so that a zone of reversed mean flow developed in the central portion of the wake. This backflow region is not attached to the surface of the wake generating body.

The present investigation can be considered as a follow-up of the study carried out by Hill et al. (1963). It focuses on the development of the near wake of an "airfoil-like" flat plate that is subjected to a strong adverse pressure gradient. The pressure distribution was tuned such that the boundary layer at the trailing edge of the plate was close to separation. This simulates the trailing-edge flow on the suction side of an airfoil near maximum lift. A zone with mean-flow reversal occurred some distance downstream of the trailing edge of the plate. As in the experiment of Hill et al. (1963), the recirculation zone was not attached to the surface of the plate, so that it can be considered a simulation of free separation in the flow about a multi-element airfoil. An important objective of this work is to provide understanding of the free separation in the wake by a thorough analysis of experimental results. The experimental data presented here go beyond the mean velocity and Reynolds stress data, and include several terms in the turbulent kinetic energy equation and spectral density functions.

2. Experimental investigation

2.1. Wind-tunnel and model geometry

The experimental facility used is an open-circuit wind tunnel at the Low-Speed Aerodynamics Laboratory of Delft University of Technology. A centrifugal fan accelerates the air which passes through a diffusing section, the settling chamber and the contraction (1:8) before it reaches the test section with dimensions 400×400 mm^2. The test section is followed by a plane diffuser that is made from perspex to allow optical access. The diffuser has a length of 920 mm and the side walls include a 15° angle. To prevent boundary-layer separation along the diffuser walls, a screen was placed at the outlet of the channel and the diffuser walls were equipped with regularly spaced slots. A straight duct with a length of 1000 mm was placed between the diffuser and the screen. The screen induces an