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Effect of free-stream turbulence on flow characteristics over a transversely-grooved surface

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ABSTRACT

An experimental investigation has been performed to study the free-stream turbulence influence on the flow over a transversely-grooved surface. Free-stream flow at 8.1 m/s with turbulence intensities of 0.5% and 4.4% have been provided over smooth and grooved surfaces. Mean velocity profiles, fluctuating velocity moments and turbulence length scales are studied using data obtained from hot-wire anemometry measurements. Introducing quasi-isotropic free-stream turbulence of 4.4% to the flow resulted in fuller velocity profiles, increased boundary layer thickness and significantly augmented streamwise turbulence intensity throughout the boundary layer in flows over both smooth and grooved surfaces. Probability density functions of the velocity fluctuation show that interaction of quasi-isotropic free-stream turbulence with wall turbulence leads to nearly-isotropic turbulence in a small portion of the boundary layer in the near-wall region; while the remaining boundary layer experiences an anisotropic turbulence. In other words, with the introduction of additional turbulence generated by the grooves, the momentum of the fluid particles is increased, resulting in better flow separation resistance. Accordingly, the flow over a grooved surface showed an increase in turbulence intensity, and hence in energy dissipation rate. This is amplified under free-stream turbulence conditions as a result of the interaction of groove-generated turbulence with free-stream turbulence in the boundary layer. The energy cascade span as indicated by the integral to Kolmogorov ratio is also widened by the grooves.

1. Introduction

Boundary layer control is an important field of fluid mechanics. Of the two main categories of boundary layer control, active and passive, passive control has attracted greater consideration as it requires no auxiliary power and hence appears more economical and simpler to implement compared to its counterpart [1]. Surface modification by using grooves is a well-known passive flow control approach. Changing the surface geometry with transversely cut grooves can be used to control flow separation [2]. Transverse grooves can serve as vortex generators introducing vortices and increasing momentum of the boundary layer region [3]. In typical boundary layer flows, the momentum of near-wall fluid particles can be reduced by both the wall shear and the adverse pressure gradient. At some point, the retarded fluid particles cannot remain attached to the wall and depart or break away from the bounding surface. The surface streamline nearest to the wall leaves the body and the boundary layer is said to separate. The added energy from vortex generation geometries enables near-wall fluid particles to resist and delay separation. Due to the large energy losses associated with boundary layer separation, separation control is of immense importance to the performance of air, land, and sea vehicles, turbomachines, diffusers, and many other engineering systems involving fluid flow. Generally it is desirable to postpone separation so that form drag is reduced, stall is delayed, lift is enhanced, and pressure recovery is improved [1].

The influence of grooves on flow characteristics is not yet fully understood. Since various types of grooves with different sizes have been studied, a wide variety of results have been reported. Depending on the combination of the groove's depth, width, and spacing, different trends are evident. Of the efforts focused on optimizing the features of these grooves, Walsh's [4,5] work, conducted at NASA Langley research center is among the most notable efforts focused on aerodynamic application of grooves. Although the majority of his efforts are focused on longitudinal grooves, he has also studied transverse grooves. He reported separation control, loss reduction, and turbulence intensity growth in the boundary layer region using grooved surfaces. Sutardi and Ching [6] reported an increase in mean velocity, streamwise and wall-normal turbulence intensities in the near-wall region immediately downstream of a transverse square groove in a turbulent boundary layer. They also confirmed that the mentioned increase propagated outwards from the wall with increasing streamwise distance downstream of the groove. Later, in two

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Nomenclature

a	length of aluminum plate in streamwise and spanwise direction, 609 mm
b	spacing between every two consecutive grooves, 3.57 mm
D	diameter of the perforated plate hole, 50.8 mm
e	width of a groove at the valley, 1.15 mm
F	flatness factor of streamwise velocity fluctuation
h	depth of a groove, 1.62 mm
L	total length of the plate in streamwise direction, 656.6 mm
N	number of sample points in hot-wire measurement, 2×10^6
OPP	orificed perforated plate
PDF	probability density function
R_u	auto-correlation function
Re_L	Reynolds number based on plate's total length, $Re_L = U_{\infty up}L/\upsilon$, 3.4×10^5
Re_x	Reynolds number based on streamwise distance, $Re_x = U_{\infty up}\delta/\upsilon$
Re_δ	Reynolds number based on boundary layer thickness, $Re_\delta = U_{\infty up}\delta/\upsilon$
S	skewness factor of streamwise velocity fluctuation
t	time, s
Tu	turbulence intensity, % degree of freedom
u	streamwise velocity fluctuation component, $u = U_i - U_{mean}$
u_{rms}	root-mean-square of the velocity fluctuations, m/s
U	streamwise velocity component, m/s
U_i	instantaneous velocity, m/s
U_{mean}	time-averaged velocity, m/s
$U_{\infty up}$	upstream free-stream velocity, 8.12 m/s
U_∞	local free-stream velocity at each streamwise section
w	width of a groove at the peak, 3.57 mm
x	streamwise distance from the leading edge of the plate, mm
y	vertical position from the surface, mm

Greek symbols

δ	boundary layer thickness, m
ε	energy dissipation rate per unit mass, m^2/s^3
η	Kolmogorov microscale, mm
Λ	integral length scale, mm
τ_Λ	integral time scale, s
υ	kinematic viscosity of air, 1.548×10^{-5} m^2/s @ STP

separate publications [7,8] they disseminated the influence of three different sized transverse square grooves and three different shaped transverse grooves (square, semicircular and triangular) on a turbulent boundary layer. They confirmed many of the qualitative results of their previous work. An increase in the mean velocity and turbulence intensity downstream of a groove was also reported in the work of Choi and Fujisawa [9]. They demonstrated the existence of quasi-stable vortex flows within the groove and speculated that a vortex is responsible for changes in the grooved flow. Elavarasan et al. [10] and Pearson et al. [11] found an increase in turbulence intensity caused by the grooves and also a significant increase in skin friction just downstream of the groove followed by a decrease below the smooth-wall value and an oscillatory relaxation to the smooth wall value. Robarge et al. [12] summarized several rules of thumb for achieving the most effective separation control by use of indented surface treatments. They also reported a study on a recessed groove placed spanwise across a NACA0015 airfoil. Laminar separation control and loss reduction were important effects of the groove on the flow. They attributed this outcome to a two-dimensional vortex structure inside the groove energizing the boundary layer. Tantirige et al. [13] used a photochromic tracer to investigate the effect of two V-shaped grooves on the turbulent boundary layer. The mean velocity profiles above the grooves were similar to those over smooth surfaces, but displaced downstream, and turbulence intensity increased immediately after the grooves. They found enhancement of heat and mass transfer rates by spanwise grooves and attributed this to energetic bursts inside the groove.

In addition to the aforementioned experimental works, there have been a number of numerical efforts studying the mechanism involved with flow over grooves. In spite of the fact that most of the turbulence models used in the numerical procedures have some deficiencies especially at flow-separated regions, Dubief et al. [14] showed the ability of numerical methods in reproducing realistic turbulent structures using a large eddy simulation technique. They investigated a rectangular groove engraved in a flat plate; which had dimensions of the order of the boundary layer thickness. Their results demonstrate an increase in the level of turbulence downstream of the groove and also a reduction in the spatial extent of coherent structures above and after the groove. In another large eddy simulation, Luo et al. [15] studied the mechanisms of a relatively wide spanwise groove for the passive control of a laminar separation bubble on the suction surface of a low-speed highly loaded low-pressure turbine blade. They stated that using a grooved surface led to shortening of the flow separation bubble, which contributed to the flow loss reduction. This was attributed to the fact that the groove made the boundary layer behind it thinner and promoted earlier transition in the separation bubble.

All of the aforementioned studies were conducted in “smooth” flow. In practice, most flows are turbulent and hence, the effect of free-stream turbulence needs to be recognized. Such is the objective of this study, where “smooth” and “turbulent” free-streams are forced over both smooth and grooved surfaces. To investigate the effect of free-stream turbulence on the flow over such surfaces, flow parameters including velocity profiles, boundary layer thickness values, and turbulence intensity profiles are presented. Moreover, to reveal further details of the flow, turbulence statistical parameters like skewness and flatness factors and also turbulence length scales have been investigated. The experimental study was performed for a flow over two flat plates with smooth and transversely grooved surfaces using hot-wire anemometry.

2. Experimental details

The experiments were performed in a closed-loop wind tunnel with a 4 m long test section. The cross section of this wind tunnel at the entrance is 0.762 m by 0.762 m. The cross-sectional area increases gradually downstream to overcome the boundary layer build-up on the wind tunnel ceiling and the floor. Consequently, the dimensions of the end of the working section are 0.762 m wide and 0.782 m high. The maximum achievable mean velocity is approximately 20 m/s in the empty working section with a