EXPERIMENTAL INVESTIGATION OF TURBULENT BOUNDARY LAYER FLOW UNDERGOING SPANWISE TRAVELING TRANSVERSAL SURFACE WAVES

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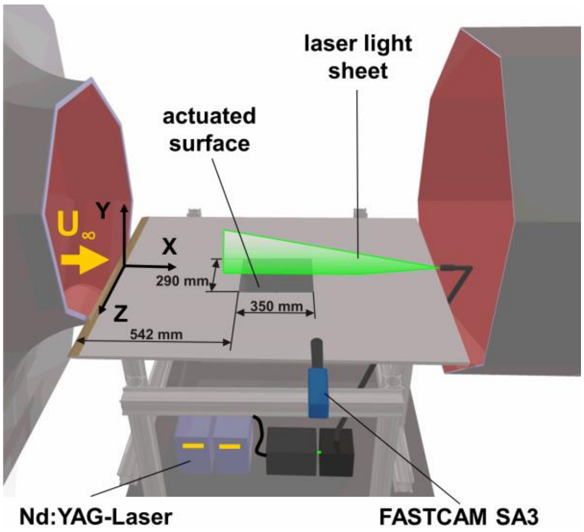
Abstract The influence of spanwise traveling transversal surface waves on the near-wall flow field of turbulent boundary layers with and without adverse pressure gradient is investigated by particle-image velocimetry (PIV) and micro-particle tracking velocimetry (μ-PTV). A detailed analysis of the velocity profile immediately downstream of the actuated surface shows a local drag decrease as well as an increase caused by the surface wave dependent on the wave parameters.

In times of global warming and lack of resources the permanently increasing traffic stream caused by globalization leads to one of today's greatest challenges in engineering, the minimization of energy consumption, e.g., in air traffic. The energy consumption of transport aircraft is strongly linked to the overall drag. Since the friction drag is with a fraction of about 50 % the main contributor to the total drag, one possibility to improve energy efficiency is to modify the near-wall flow field by active flow control concepts. Besides direct local control methods, e.g., blowing and suction, there are global control methods based on changing the near-wall flow by introducing spanwise and/or wall-normal velocity components into the near-wall flow field. Several experimental and numerical investigations using various approaches such as spanwise oscillation, plasma actuated waves, or transversal surface waves with wall deformation have been performed to prove the efficiency of this active control method (Karniadakis and Choi [1]). For instance, Tamano and Itoh [2] have shown that a spanwise traveling transversal surface wave with wall deformation can reduce the friction drag of a turbulent boundary layer by 13 %. Numerical investigations by Klumpp et al. [3] considering a similar approach achieved a drag reduction by approximately 9 % with particular combinations of frequency, wavelength, and amplitude whereas other parameter setups even led to drag increase. These model-based results imply that a spanwise traveling transversal surface wave cannot only be used to reduce the wall-shear stress. In contrast, it offers new possibilities to control flow separation caused by a positive pressure gradient by increasing the friction drag.
To confirm this hypothesis and to investigate the influence of the wave parameters on the variation of friction drag, a detailed experimental study of the near-wall flow structures in the boundary layer is essential. Therefore, the near-wall flow field of a turbulent boundary layer with and without an adverse pressure gradient influenced by spanwise traveling transversal waves is examined experimentally by PIV (particle-image velocimetry) and μ-PTV (micro-particle tracking velocimetry).

a) 

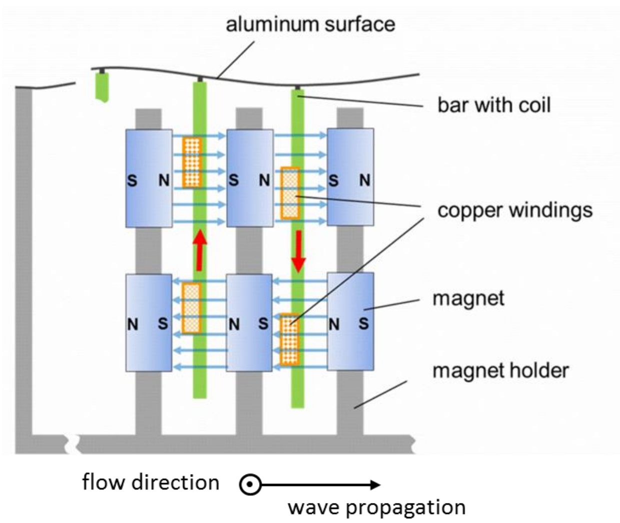
b) 

Figure 1. Sketch of the experimental setup (a) and the actuator system (b)

The experimental setup consists of a flat plate (L = 1700 mm, W = 1400 mm) with a tripping wire (d = 0.5 mm) downstream of the leading edge to force the transition from laminar to turbulent flow at a constant position. Upstream of the moving surface the turbulent boundary layer is fully developed. The maximum momentum thickness is 0.3 % of

the distance between the tripping wire and the oscillating wall. The center of the flat plate is equipped with a flush-mounted insert where an aluminum surface of 0.3 mm thickness (l =350 mm, w = 290 mm) can be actuated by a spanwise traveling sinusoidal wave with wall normal deflection (Figure 1a). The transversal wave is imposed on the aluminum surface by an electromagnetic actuator system developed by the Central Institute for Electronics (ZEL) of the Forschungszentrum Jülich. It consists of 10 bars with a lateral spacing of 20 mm aligned in the streamwise direction which are glued to the lower side of the sheet. Each bar is equipped with a copper coil of 200 windings and is located between permanent magnets. The actuator system is operated by a control unit that allows the generation of transversal surface waves with an amplitude up to A = 0.5 mm and frequencies in the range 0 Hz < f < 160 Hz (Figure 1b).
To obtain the velocity distribution of the complete boundary layer, a standard 2D-2C PIV technique is used. The local friction drag is determined by the velocity profile in the viscous sublayer ($y^+ \leq 5$) which yields the wall-shear stress $\tau_w = \mu \partial u/\partial y \cong \mu du/dy$. Due to the very small thickness of the viscous sublayer and the low particle density in the near-wall region a high resolution μ-PTV measurement system including a long distance microscope according to Kähler et al. [4] is applied to resolve the near-wall velocity profile.
First experiments were conducted in a low speed wind tunnel at three Reynolds numbers of Re_Θ = 1200, Re_Θ = 1660, and Re_Θ = 2080 based on the momentum thickness. The dimensional frequency and wavelength of the surface wave were kept constant, whereas the amplitude was varied: f = 81 Hz, λ = 160 mm and A = 0.25, 0.30, and 0.375 mm. Figure 2 shows the results of the local drag reduction (*DR*) defined as the relative wall-shear stress difference between the modified and the non-impacted flow immediately downstream of the actuated surface. For comparison, the *DR* values are plotted into an extended version of the *DR*-T^+ diagram of Tamano and Itoh [2] where T^+ defines the wave length in inner coordinates. The comparison confirms the findings of Tamano and Itoh [2] in the sense that at low T^+ values a drag reduction is achieved while at higher T^+ the drag reduction effect decreases up to a negative drag reduction, i.e., drag increase, at a Reynolds number of Re_Θ = 2080.

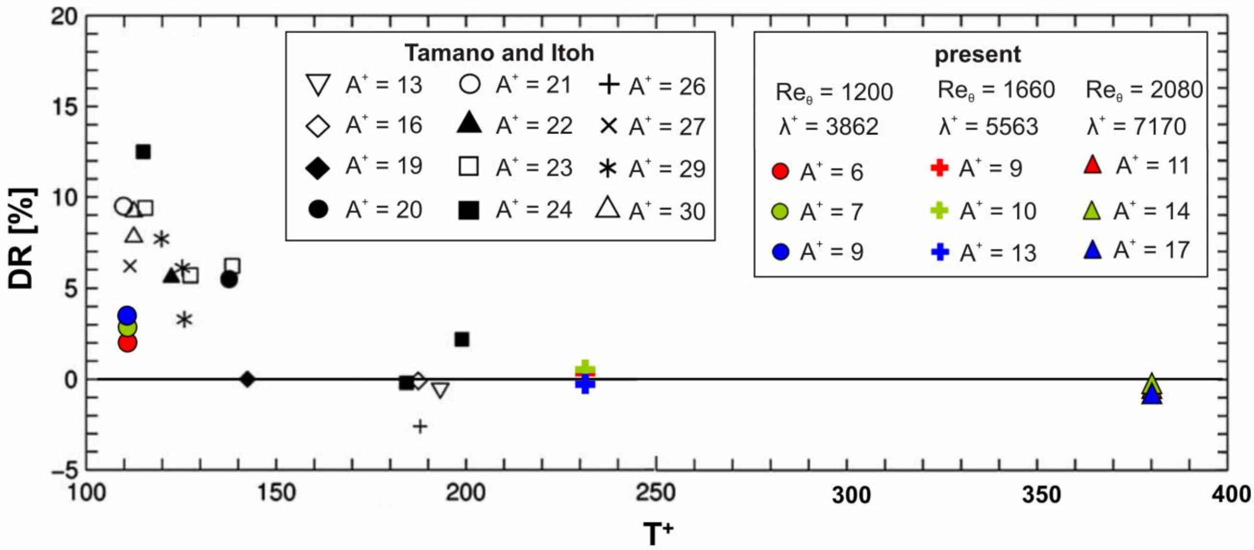


Figure 2. *DR* versus T^+ showing the present results and the findings of Tamano and Itoh [2]

To gain a better understanding of the underlying physical mechanisms and flow phenomena a detailed investigation of the flow field above the actuated surface is performed by synchronizing the PIV respectively μ-PTV technique and the wall movement. Furthermore, an adverse pressure gradient is imposed on the turbulent boundary flow to investigate the possibility of the drag increasing effect of spanwise traveling surface waves at certain wave parameters to prevent flow separation. These results will be discussed in the conference contribution.

References

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