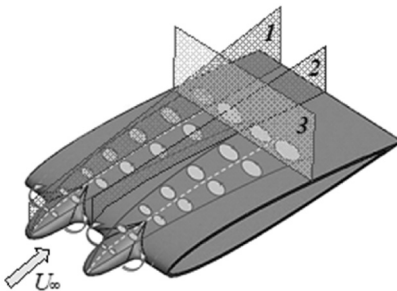


## PARTICLE IMAGE VELOCIMETRY OF PERIODIC COUNTER-ROTATING VORTICAL SYSTEMS IN THE LONGITUDINAL AND TRANSVERSAL PLANES RELATIVE TO THE MAIN FLOW DIRECTION

Natural vortices (whirlpools, tornadoes) are well known as structures of various flows with the ability to concentrate energy and transport it over significant distances, maintaining self-sustaining stability over a relatively long period of time. In engineering, the efficiency of vortex interaction with adjacent flow areas has led to the widespread use of vortex generation in engineering, in particular, in thermal power engineering to intensify heat and mass transfer processes, as well as in hydrodynamics for flow control. One of the most obvious examples of targeted vortex generation is the bumps on the leading edge of the fins of a humpback whale [1], which increase its maneuverability by expanding the range of angles of attack (AoA) of the flow without separation due to the formation of a regular structure of longitudinal vortices with paired opposite rotation in the boundary layer, also known as counter-rotating vortex pairs (CRVPs) or, because of the shape of their cross-section, like kidney-shaped vortices (Figure 1).



*Figure 1 – CRVP vortical structures formed by leading-edge tubercles on the windward wing surface.*

The advantages of the leading edge tubercles are the process of enhancing vortex generation as the AoA increases, which was studied in detail by the author using a 2D Time-Resolved Particle Image Velocimetry (TR-PIV) measuring system (Figure 2) installed in a certified closed-loop wind tun-

nel of the College of Engineering of Zhejiang Normal University (Fig. 3) and applied to several sections of the rectangular wing model parallel to the flow direction and located along the plane of symmetry of the tubercle 1 (Figure 1) or in the median plane 2 between two adjacent tubercles with their different lengths (from 2% to 35% of the chord) and different shapes, including curved relative to the AoA [2–5].

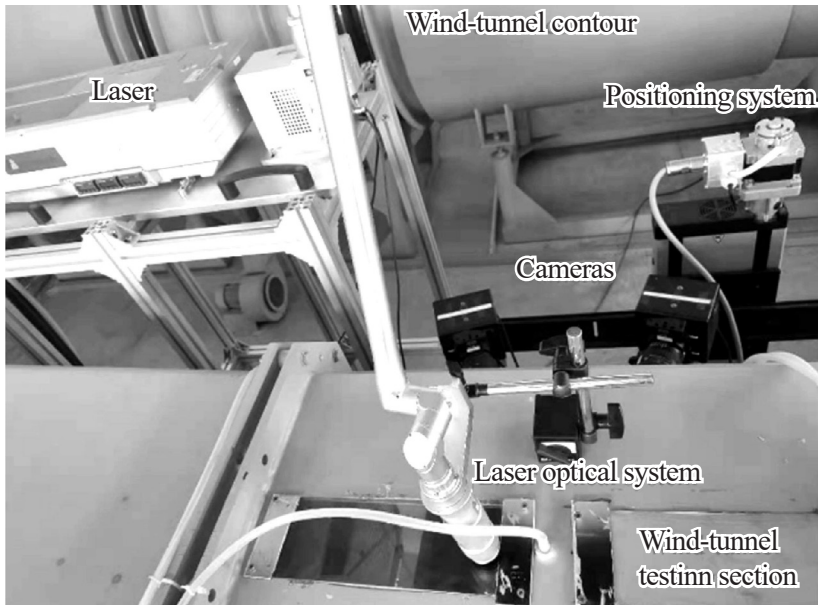


Figure 2 –TR-PIV measuring system of the College of Engineering of Zhejiang Normal University (Zhejiang province, Jinhua, China)

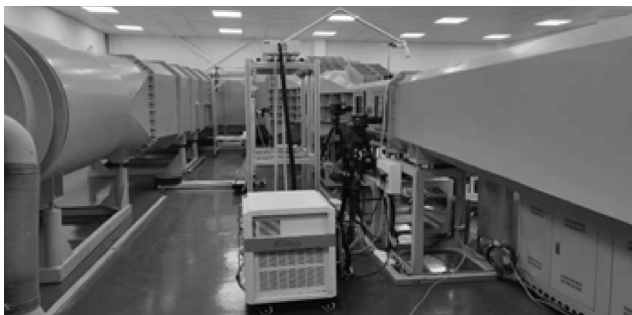
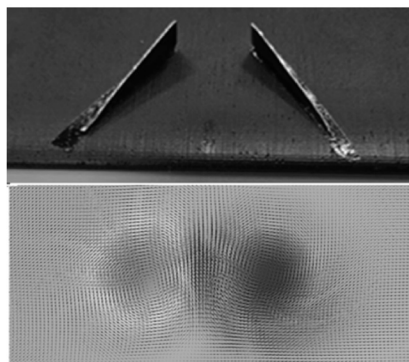
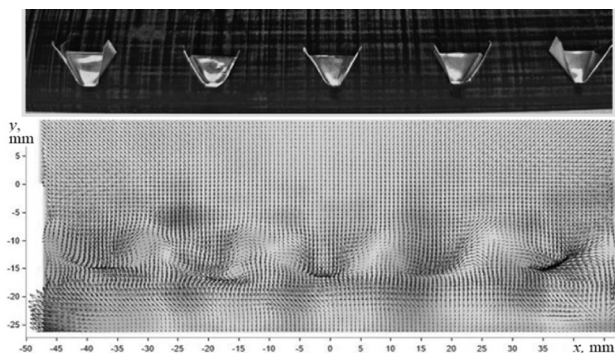


Figure 3 – Closed-loop wind tunnel of the College of Engineering of Zhejiang Normal University (Zhejiang Province, Jinhua, China)

In this study, a more traditional type of vortex generators (VGs) in the form of paired triangular wings (Figure 4,5) was used as a geometrically different, but physically similar alternative for comparison with "tubercles", and a series of three-dimensional TR-PIV measurements were performed in plane 3, transverse to the direction of the undisturbed flow, in several sections along the chord, which involves the use of two video cameras symmetrically positioned both relative to the main direction flow and relative to the measurement plane. In addition, by providing direct information about the structure of the secondary streams in plane 3, which are significantly weaker than the main stream, the technology involves careful adjustment of both the cameras and the thickness and intensity of the flat laser beam.



*Figure 4 – CRVPs formed by one pair of delta-winglet's VGs mounted 10mm from the leading edge on the windward surface of the wing (here and on the Fig. 5 vectors show the distribution of secondary velocity in plane 3, color*



*Figure 5 – CRVPs formed by an array of twin delta-winglet's VGs mounted similar to the Fig. 4*

The conducted TR–PIV measurements have convincingly shown that even at pre–separation AoA, the leading-edge tubercles are significantly weaker VGs compared to twin delta-winglets of comparable transverse dimensions when installed with the same 20 mm pitch along the span, but, nevertheless, they significantly regularize the turbulent boundary layer, making it more spatial, and this effect is preserved in the near wake even at small tubercle lengths of about 2% of the chord. Thus, the geometry of the leading edge has a significant effect on the flow around the wing as a whole and the choice of its rational shape is an important direction for further optimization of the lifting and control aerodynamic surfaces. In addition, a significant methodological achievement of this study is the demonstration of the possibility of measuring the characteristics of weak secondary flows in the transversal plane 3, which implies careful positioning of the two chambers and the plane of the laser beam in the test section of the wind tunnel.

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