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Volumetric Velocimetry Study in a Transitional Wall Jet Flow with Passive Flow Control via Flaps

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Abstract Birds are remarkably good flyers and show very special adaptations in their wings for stall delay. The pop-up of some cover feathers during starting and landing gave the idea for the present study to investigate the influence on a wall jet when inserting an array with flaps made of elastomer foil. In a wall jet with $Re = 420$ a flat plate and two different flap arrays (with a foil thickness of 100 and 200 μm) are measured by a time resolved 3D scanning PIV with 20 laser sheets. 2-dimensional analyses show the forming rollers between the jet flow and the surrounding fluid with a fundamental frequency of 13-14 Hz and the characteristically vortex pairing. By inserting the flap array the jet wall-normal spreading gets intensified and the vortex interaction process results in cooperative formation of larger vortices. The 3-dimensional analyses verify these results and show high 3-dimensional vortical structures which are growing when passing over a flap array. In case of the inserted flap array the vortex pairing process was delayed and accumulation of spanwise vorticity was forced to happen over the first rows of flaps, thus forming the larger structures. Already the used flap array configurations showed a significant impact influence on the jet evolution and the non-linear instabilities. Further investigations will analyze the influence of more parameters as the flap geometry or the distance to the jet flow and nozzle outlet.

1. Introduction

Birds developed their flight technique over a period of approximately 150 million years. In addition to anatomical modifications like their very light skeleton, birds have very sophisticated wings with several adaptations for stall delay at high angles of attack. It was discovered, for instance, that during landing and also starting some of the cover feathers pop up when the angle of attack is very high. In Fig. 1 this effect is visible on the wing of a flying skua. Assumingly, these feathers prevent the growth of the vortex which is formed at the trailing edge of the wing and causes stall as schematically shown in Fig. 1 on the right side. [2, 4, 7, 8]

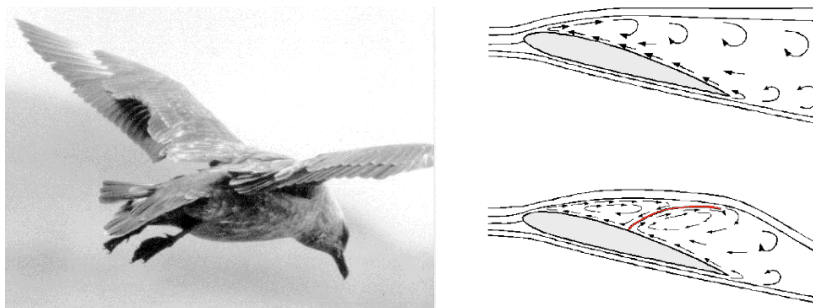


Fig. 1 On the left side a flying skua (*Stercorarius*) with lifted cover feathers is shown, on the right side a cross section of a wing profile demonstrate the effect of still attached flow by the uprising feathers

This effect might prove very useful in aerodynamics and still needs to be investigated further as there is only little information about the actual influence of structures which pop up. In this study a wall jet above a flat

plate is used as a well-defined flow to compare the influence of flaps along the flap plate on the shear-layer roll-up process. The jet mimics the shear layer that develops in the thin separation bubble along a wing profile when the flow undergoes transition to stall. By varying the wall-normal distance of the jet mean flow axis relative to the wall it is possible to modify the character of the roll-up process with respect to the position and arrangement of the flaps. 3-dimensional flow measurements were carried out to investigate the roll-up process and the non-linear instabilities with and without the presence of the elastic flaps.

2. Material and Methods

2.1 Experimental Setup

The experiments are performed in an octahedral water tank. A nozzle with a rectangular cross section (spanwise width $L = 120$ mm, height $d = 5$ mm) and a high contraction ratio of 30 generates a jet flow that develops along a flat plate. The plane wall is placed flush with the bottom wall of the nozzle exit and is oriented parallel to the flow. The Reynolds number is defined with half of the nozzle height d , the maximal velocity u and the kinematic viscosity of water ν_{water} . A Reynolds number of 420 is used for the experiments which results in a flow velocity at the nozzle outlet of 0.17 m/s. The nozzle flow is driven by a linear actuator (MOOG, AC-Servo-Actuator, Böblingen, Germany) which moves a piston and generates a defined flow stream.

The bottom wall is a 5 mm thick plexiglas plate that was sprayed with dim black color to be non-reflective and sanded afterwards to make the surface as smooth as possible. A flap array made from flexible elastomeric foils is embedded along the bottom plate to mimic the presence of feather-like structures, similar as used by Brücker and Weidner in [1] (see Fig. 2). The material parameters of the silicone are given in form of the shore hardness A of 30, which is about 3.04 MPa. Two different foil thicknesses of 100 and 200 μm are used for the experiments and positioned with an angle of 45° to the bottom plate to assure an interaction with the fluid as shown in Fig. 2. The flaps have a height L of $1 d$ and a width W of $0.6 d$ with a spanwise pitch of $0.6 d$. In streamwise direction the successive rows have an interspacing of $2 d$ to match approximately the fundamental wavelength of vortex roll-up, see below. This was motivated by the results found in Brücker & Weidner (2014).



Fig. 2 Used flap array with transparent foil flaps of a height of $1 d$ and a width of $0.6 d$ with a spanwise pitch of $0.6 d$ and a streamwise interspacing of $2 d$. The first row is positioned at $8 d$ downstream of the nozzle exit. As illustrated in the right sketch, the flaps are elevated from the wall with a deployment angle of 45°

In Fig. 3, the experimental setup is shown schematically and in pictures of the actual arrangement. A platform is affixed to the nozzle with the flap array (indicated in red). The upper part at the nozzle outlet can be changed to perform measurements with a flat plate for a flow characterization. The nozzle and platform are affixed in an octahedral tank with a diameter of 290 mm and a height of 590 mm. A high-speed pulse Nd:YLF-Laser (Litron Lasers, 30 mJ at 1 kHz) is used in combination with a rotating polygon mirror built up on 40 facets, which produce a set of 20 parallel and partially overlapping light sheets per volume scan at 395 Hz. Each light-sheet has a thickness of ca. 3.5 mm and an overlap of approximately 65 % with the previous and the subsequent one to apply the method of isotropic voxel reconstruction described in Brücker et al. [1]. A high-speed camera (Phantom 12.1, Vision Research, resolution at $1024 \times 608 \text{ pix}^2$ at 10 kHz) captures the light sheets (indicated in dark green, Fig. 3). To compensate the perspective distortion a telecentric lens is mounted on the camera which is synchronized with the laser using a sequencer at 10,000 fps. This leads to an illuminated volume of approximately $81.3 \times 39.4 \times 25 \text{ mm}^3$. Particles with a mean diameter of $100 \text{ }\mu\text{m}$ (Vestosint, Evonik Degussa GmbH) are dissolved within the water of the tank for Particle Image Velocimetry (PIV) analysis.

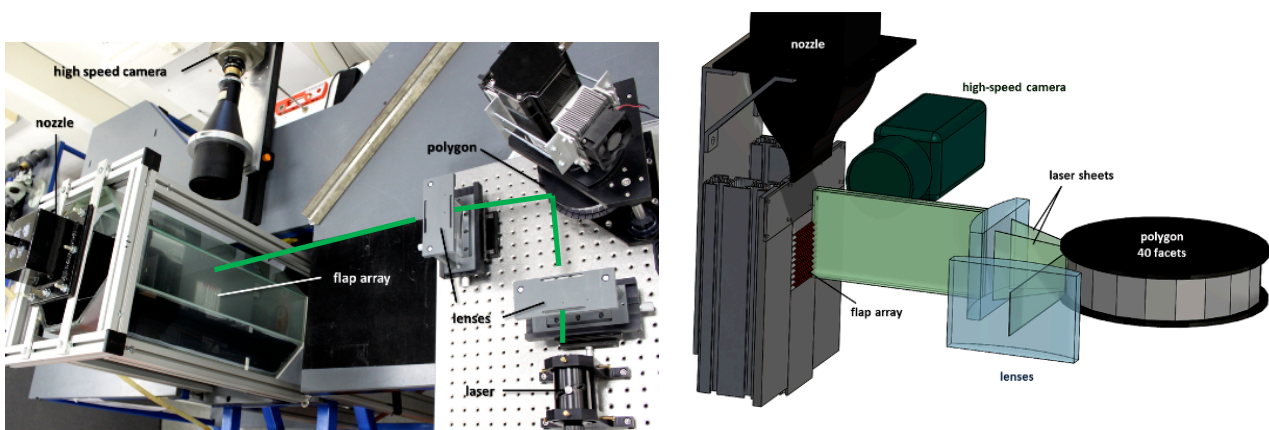


Fig. 3 Experimental set-up (left) and a schematic drawing (right) with the flap array embedded in a smooth platform at a distance of $8 d$ behind the nozzle outlet. A laser sheet is focused by a lens and split into 20 sheets by a rotation polygon with 40 facets. A synchronized high speed camera records the individual laser sheets for further analysis

2.2 Data Analysis

The post processing of all experimental data is performed with a self-written program in Matlab R2013a (8.1.0.604, MathWorks) and DynamicStudio Version 3.31 (Dantec dynamics, Ulm, Germany).

In a first step, the scanning planes are analyzed only in certain sheet positions using standard 2-dimensional PIV analysis (DynamicStudio, interrogation area size of 32×32 pixels, overlap of 75 %). After identifying the characteristic events from the 2-dimensional planes, the full data set is reconstructed for a defined time-span to analyze the flow evolution more in detail in 3-dimensional and in temporal evolution. Therefore the voxel volume defined by 19 overlapping laser sheets is reconstructed. The first sheet is not used because it has a very high laser power in order to distinguish the different sheets which is necessary. Because of the laser sheet overlap, the same particles are visible in minimally four different sheets. To recalculate the position of

each particle, a Gaussian grey level distribution is applied. A reconstructed voxel volume is exemplarily shown in Fig. 4. Afterwards the volumes are imported in DynamicStudio in order to apply the least square matching function. The interrogation cuboid is 37x37x37 pixel in size. To visualize the 3-dimensional results TECPLOT 360 (Tecplot Inc.) is used.

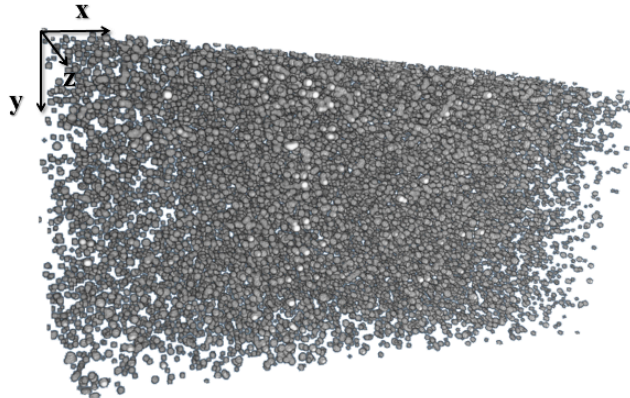


Fig. 4 Reconstructed voxel volume of one time step with visible particles with the dimensions of 81.3x39.4x25 mm

3. Results and Discussion

3.1 2-Dimensional Analyses

To illustrate the overall flow pattern in selected phases of the flow we used the method of image-overlapping to mimic multi-exposure pictures of the flow from the recordings. Fig. 6 displays such images in form of multi-exposure images of eight overlying images from the scanning recordings. In image (a), the particle flow over the plain flat plate downstream of the nozzle exit is shown. The particle path lines indicate the roll up process above the jet flow with the surrounding fluid. Equally spaced counter-clockwise rotating vortices called roler are formed along the jet-axis with a wavelength of about $2.4 d$. The observed vortex roll-up frequency of about 13-14 Hz is displayed also in Tab. 1. In the boundary layer over the flat plate, small hairpin vortices are formed immediately on the luv-side of the roler, which rotate counterclockwise. Together with the roler, they display a zig-zag pattern. As the hairpin vortices grow in size the jet is deflected upwards and so is the roler. As a result of the vortex interaction of the roller and the near-wall structure both vortices rotate around each other thus decelerating the hairpin vortex until flow separation is observed. Because of its axial momentum the roler travels further downstream and is partially sucked around the hairpin vortex. This vortex interaction leads to a high wall-normal component of velocity and has also been seen in wall jet measurements by Levin et al. (2005) and Skupsch et al. (2012).

In image (b) in Fig. 6 the particle flow with 100 μm flaps is shown. Analogous to the jet flow over a flat plate, rolers are formed in the shear layer of the jet and the ambient fluid. The spacing between rolers seems do have decreased and the flow field changes when reaching the positioned flaps (indicated in red). The flaps are mainly inclined towards the wall and are just lifted upwards when a roller and hairpin are passing. A

phase shift in this motion between the flap rows is seen as the vortex reaches each row at different times during the recorded sequence. The formed hairpin vortices are rolling over the bended flaps which results in a deflection of the jet flow in wall-normal direction. Together with the roller, this results in a larger spreading than in case of the plain wall jet. Here the vortex pairing process at the outer shear-layer seems to occur at the position of the first flap rows and is therefore delayed when comparing with the previously discussed case.

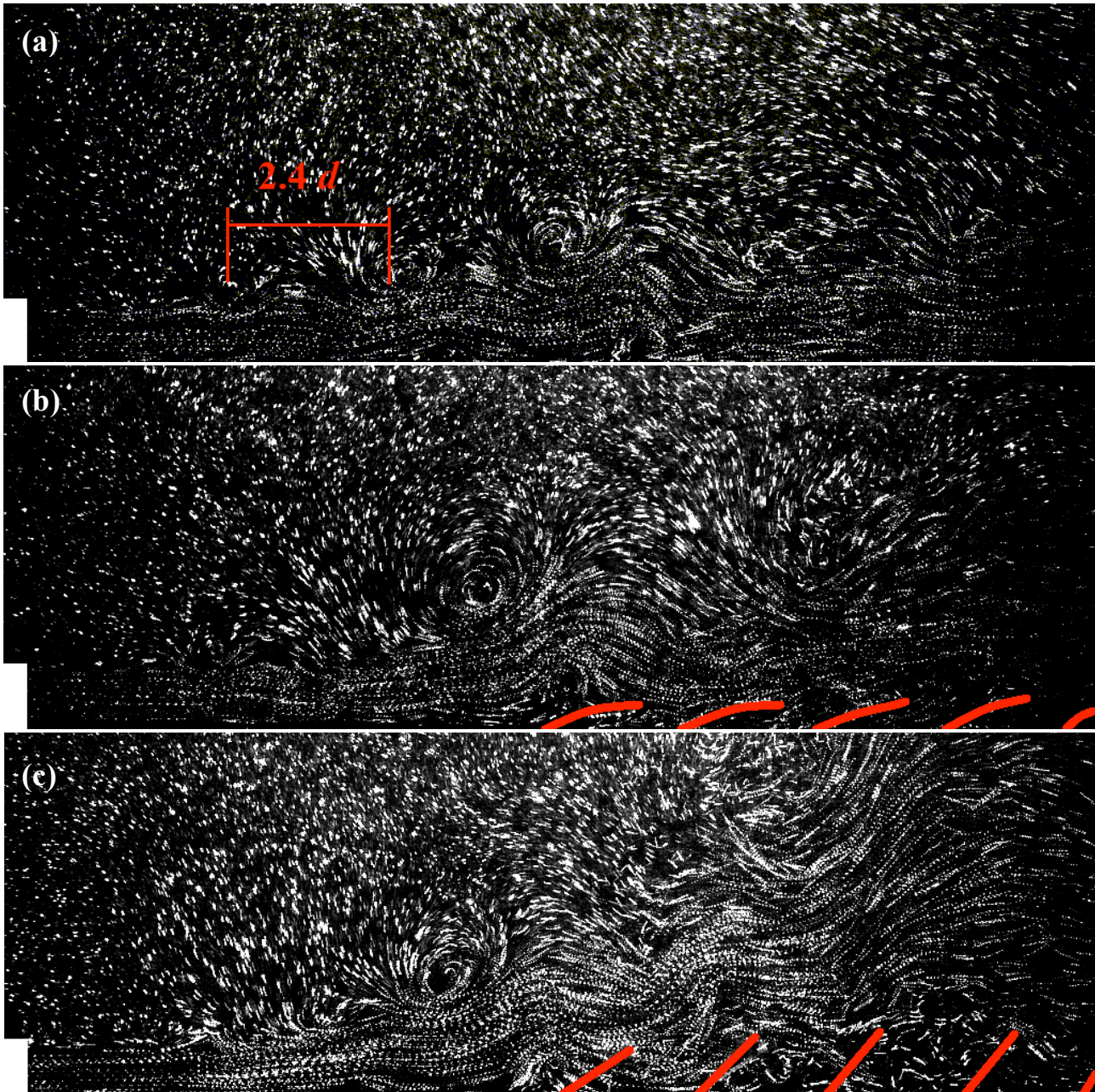


Fig. 6 Multiple-exposure imaging from eight successive scans in one selected plane representing the 2-dimensional flow field downstream of the nozzle exit (indicated as the white rectangular box in the left corner), the particles show the path lines in the flow field. In (a) the nozzle flow over the flat plate is shown with periodic roll-up of vortices in the shear layer at 13 Hz and a spacing about 12 mm. By inserting thin flaps (b) the flow field is altered and subharmonic instabilities are promoted. In (c) the 200 μm flaps are used which generates a lift-off of the jet away from the plate and also seems to alter the vortex generation

When inserting the flap array with a thickness of 200 μm , the change of flow field appearance is more prominent. The flaps in the first row bend with the oncoming wall jet but are not tilted towards the wall as much as seen for the thinner flaps. The forming hairpin vortices have to roll over the rather stiff flap and thus get a high wall-normal deflection. Furthermore, the particles path lines indicate a more pronounced spreading of the jet in wall-normal direction with increased entrainment from the ambient fluid. Again the vortex pairing seems to be delayed to the position of the first flap rows.

Tab. 1: Results for the wall jet over a flat plate at Re 420

vortex shedding frequency	13-14 Hz	$f^*d/u = 3.8 - 4.1$
fundamental wavelength vortices	12-13 mm	$\lambda \approx 2.4 - 2.6 d$
distance from nozzle to vortex pairing	ca. 40 mm	$xc/d \approx 8 d$

For a further comparison, the 2-dimensional flow fields analyzed with DynamicStudio are averaged over a period of 21 shed vortices (1.5 seconds) to get a time average representation of the global behavior. In Fig. 5, the flow fields are shown as color plots of the velocity magnitude for the three different configurations (flat plate (a), thin flaps (b) and thick flaps (c)). In all three cases, the spreading of the jet flow is visible at some distance from the nozzle.

The velocity distribution in the wall jet over the plain wall seems to be attached for the complete region of interest. When inserting a flap array the wall jet is elevated and spread out, thus the velocity changes are smoother. Particularly in case of the thick flaps, flow is separated and a dead water flow region is formed between the rows of flaps.

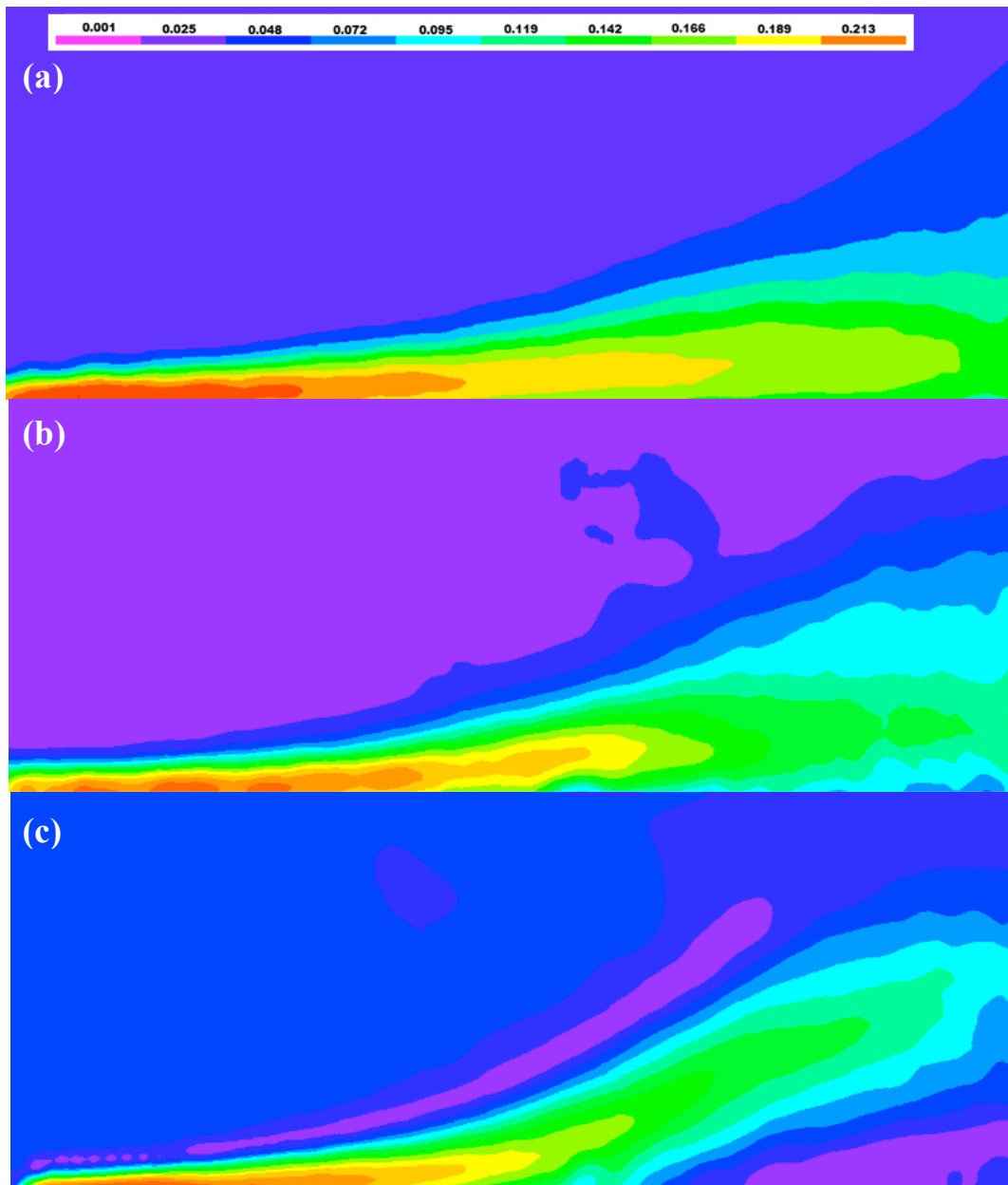


Fig. 5 Magnitude of in-plane averaged velocity of about 600 time steps for the flat plate (a), the thin flaps (b) and the thick flaps (c). By inserting the flaps the jet becomes wider and the velocity distribution more homogeneous. In case of the thick flaps the wall jet gets a high wall-normal deviation

3.2 3-Dimensional Analyses

For each configuration, a 3-dimensional analysis is done for selected time-spans when the large burst-type vortex is formed (analogous to the multiple-exposure images). The time step for the flat plate (see Fig. 6 (a)) displays large vortical structures of z-vorticity, so in spanwise direction of the rollers. Because of the used analyze method the voxel volume is reduced at the borders and the hairpin vortices are not visible. The isosurface indicates the rollers, which seems to be connected in streamwise direction with smaller secondary structures. Further downstream a structure in the middle of the volume is formed. This indicates the event of vortex pairing and interaction with the counter rotating hairpin vortex which generates high wall-normal

motion. When inserting the flap array with a foil thickness of 100 μm (Fig. 6 (b)) the roler formation upstream of the first flap row is more pronounced and clearly visible with some structure in streamwise direction, however its appearance is delayed with respect to the plain wall. The rolers positioned over the flap array interact with each other and form a large vortical structure that lifts off from the wall.

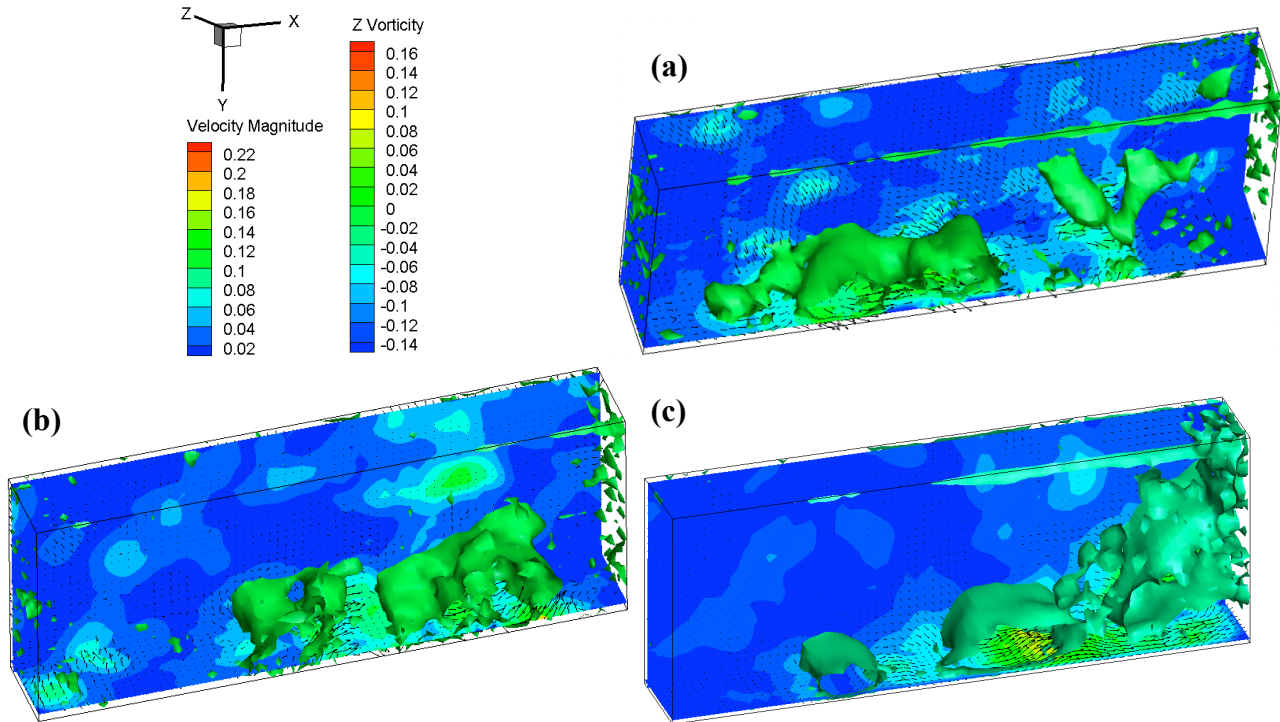


Fig. 6 3-dimensional time steps for the flat plate (a), the thin flaps (b) and the thick flaps (c). At the walls is displayed the velocity magnitude with vector arrows, as well as the z-vorticity with isosurfaces to make the rolers visible

In case of the analyzed time step, see Fig. 6 (c) with the thick flaps the vortical structures are separated into three different structures. The first occurring roler has no connection to the bigger structure, which is visible when reaching the first flap row. Here the vortex pairing seems to happen further downstream from the nozzle exit. The roler had grown into an even bigger structure with high wall-normal. In the spanwise direction, three flaps in each row are influencing the jet flow which is slightly seen in some waviness of the secondary vortex structure in (b) and (c). For all three voxel volume some errors are visible in the velocity magnitude as well as in the z-vorticity at the borders of the volume.

When comparing these results with the numerical results of the Blasius wall jet from Levin et al. [5] in Fig. 7, some of the observed features can be found in similar shape and arrangement within the jet.

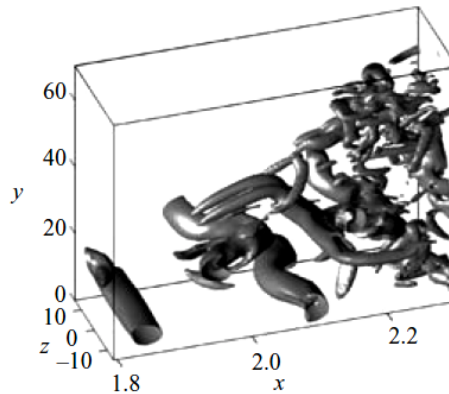


Fig. 7 Development of the vortical structures in one fundamental frequency with isosurfaces of λ_2 [5]

A further analysis of the time-series recordings is currently under way to evaluate the temporal evolution of flow structures during the mutual interaction process.

3.3 Conclusion and Outlook

The wall jet over a flat plate is investigated using Time-Resolved PIV and 3D Scanning PIV. Rollers and hairpin vortices are formed and interact with each other to form larger structures that elevated from the wall into the ambient fluid which is typical behavior as seen in the literature. Of major interest is the behavior of the flow when inserting small flaps along the wall that interact with the flow. Previous experiments within our group on cylinder and airfoil wakes have shown the beneficial effect of the flaps on reducing lift and drag-force fluctuations and therefore reducing the risk of aerodynamic flutter. The wall jet studies allow us to investigate the interaction of shear layer rollup and the flaps in a more defined way. The first results with arrays of soft flaps show that the interaction process delays the vortex pairing process further downstream, however, then the vortical structures increase in size. By making the flaps stiffer this effect is strengthened. Ongoing measurements with variations in parameters such as flap geometry, material, equilibrium angle and position as well as the position of the flaps relative to the nozzle exit will be carried out. The goal of the study is a more fundamental understanding of the interaction with the flaps in light of possible mode locking and influence on the non-linear process of vortex pairing as observed in dynamic stall experiments [1].

4. Acknowledgements

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