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LARGE EDDY SIMULATION OF SWIRLING JET FLOW UNDERGOING VORTEX BREAKDOWN INCLUDING NOZZLE MODELING

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1 Scientific background and objectives

Swirling jets undergoing vortex breakdown occur in many technical applications, e.g. vortex burners, turbines and jet engines. At the stage of vortex breakdown the flow is dominated by a conical shear layer and a large recirculation zone around the jet axis. This highly nonlinear flow state additionally features hysteresis behaviour, bistability, i.e. different flow states occurring at the same values of control parameters, and bifurcation. Despite decades of intense research there is still no consensus found about the underlying mechanism leading to this abrupt change of flow [1]. In their experimental investigation Liang & Maxworthy [2] suggest the existence of a pocket of absolute instability in the wake of the jet triggering a global mode overwhelming the whole flow. In a recent investigation [3] a co-rotating, counter-winding helical mode is found with its 'wave-maker' located in the inner region of the jet. A preceding investigation of our group [4] showed that our DNS/LES code CONCYL is capable of capturing the fundamental physics of swirling jets undergoing vortex breakdown, see also [5]. The results showed good qualitative agreement with experimental data for a self-excited and a forced jet. The fact that the breakdown occurred directly after the inflow plane was considered to possibly prevent the development of self-excited instabilities due to the presence of an inflow sponge layer.

To account for more realistic inflow boundary conditions, in the present work a rotating nozzle is included in the computational domain [6]. A $Re=5000$, $Ma=0.6$ swirling jet with the azimuthal velocity component as high as the streamwise component (swirl number $S=1.0$) is investigated by LES along the lines of [4]. The simulation is done on a domain with size $L_r \times L_z = 10R \times 20R$ in the radial and streamwise directions with a nozzle of length $L_n = 6R$ included, where R is the nozzle radius. The grid resolution is $N_\theta \times N_z \times N_r = 36 \times 180 \times 216$ grid points. Our work is in progress and preliminary results are presented and will be compared to recently published results in the literature.

2 Simulation methodology and Results

Our simulation code, recently parallelized for massively parallel architectures, solves the compressible Navier-Stokes equations in cylindrical coordinates [7]. Spatial derivatives are calculated using high-order finite difference schemes (up to 10th order) for the streamwise and radial directions while a Fourier spectral method is employed in the circumferential direction. Time integration is done applying a 4th-order 6th-stage LDDRK scheme developed for investigating aeroacoustics of jets [8]. As a subgrid scale model we use our in-house Approximate Deconvolution Model (ADM). Boundary conditions are chosen in analogy to [4] and the nozzle is modelled as an isothermal wall.

Figure 1 shows the development of $\langle \theta, t \rangle$ -averaged profiles for all three velocity components. At the jet axis a deficit in the streamwise velocity develops, with the profile changing from jet- to wake-like within the downstream part of the nozzle indicating beginning vortex breakdown. At the same downstream position the azimuthal velocity profile start to deviate from the initial solid-body rotation. Behind the nozzle both velocity components are largest within the azimuthal shear layer accompanied with a rising radial velocity component related to the massive spreading of the jet. The recirculation is strongest around $z = 7.5R$ representing the core of the recirculation bubble, which has a length of about $2R$. Within the nozzle pressure and density (not shown) increase in the downstream direction, adapting to far-field values right behind it.

Instantaneous contours of the streamwise, w , and azimuthal, v , velocity components are plotted in figure 2. The local recirculation near the centerline is much stronger compared to the averaged data. The rapid breakup of the conical shear layers is visible. In the recirculation zone the fluid counter-rotates with respect to the mean flow, an effect also reported by Facciolo et al. [9]. Compared to results stated in [4] the spreading angle of the jet is larger.

An analysis of the instantaneous stagnation point location shows that it travels upstream, shifting up- and downstream around $z = 6.5R$ precessing around the jet axis in a counter-clockwise manner. Iso-surface plots of the pressure show a helical, counter-winding mode, co-rotating with the mean flow, similar to structures observed by Billant et al. [10] for the post-breakdown stage.

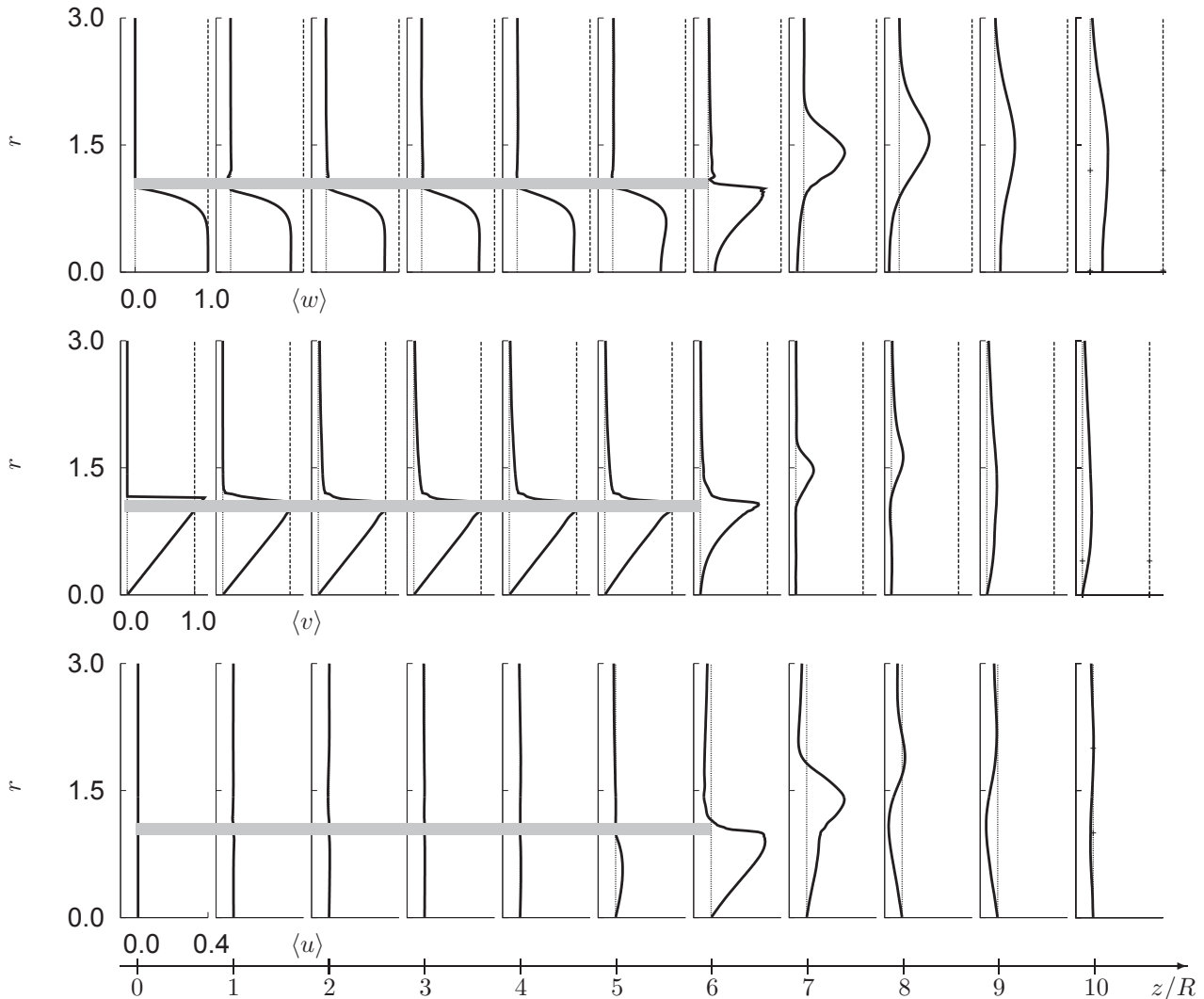


Figure 1: Axial development of mean streamwise, azimuthal and radial velocity (top to bottom). The grey bar indicates the position of the nozzle wall.

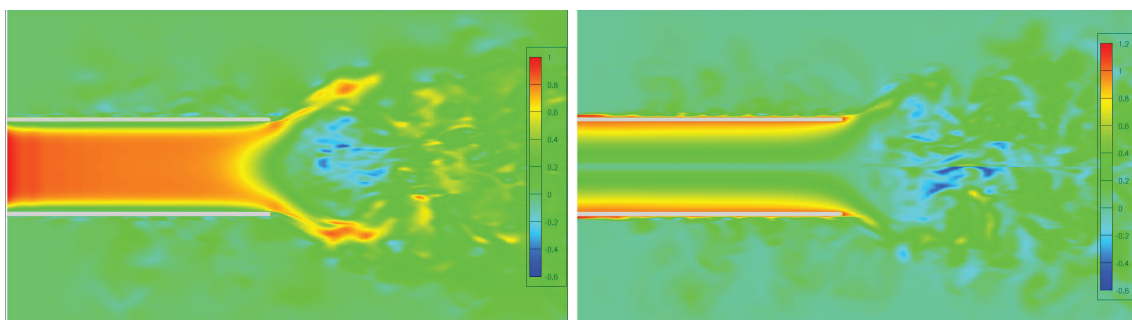


Figure 2: Contour plots of the instantaneous streamwise (left) and azimuthal (right) velocity at 20 flow-through times.

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