Density Field Reconstruction of an Overexpanded Supersonic Jet using Tomographic Background-Oriented Schlieren

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Abstract

In this study, a Tomographic Background-Oriented Schlieren (TBOS) technique was used to reconstruct and visualize the three-dimensional density field of an overexpanded supersonic jet. An experimental setup was devised around a sub-scale rocket nozzle in which four cameras were set up in an angular configuration. Measurements were taken of the flow at various nozzle pressure ratios (NPR), corresponding to different flow regimes during the start-up and shut-down phases of rocket nozzles. The reconstructed density fields reveal the expected shock structures.

Background

The unsteady rocket nozzle flow characteristics occurring during the start-up and shut-down phases are difficult to predict, leading to current nozzles that are over-designed to withstand the critical lateral loads. A better understanding of the flow during these phases could help optimize their design and reduce their mass.

BOS working principle

The Background-Oriented Schlieren (BOS) technique uses light ray deflections through refractive index changes in a fluid to visualize density gradients [1]. A BOS setup consists of a background pattern, a medium with density gradients, and an imaging device. By comparing "flow on" and "flow off" recordings of the background, an apparent shift in the background pattern due to the refraction of light can be extracted, which is directly proportional to the line-of-sight integrated density gradients of the flow.

Density field reconstruction

BOS is first used to extract the density gradients from various projections. Using these projections, a Poisson equation is solved and the line-of-sight integrated density field is obtained. Then, the filtered back-projection (FBP) and simultaneous algebraic reconstruction technique (SART) are used to reconstruct individual two-dimensional density slices of the flow. These are subsequently stacked to reconstruct the (quasi-) three-dimensional density field. Fig. 1 graphically shows the steps taken to reconstruct the density field.

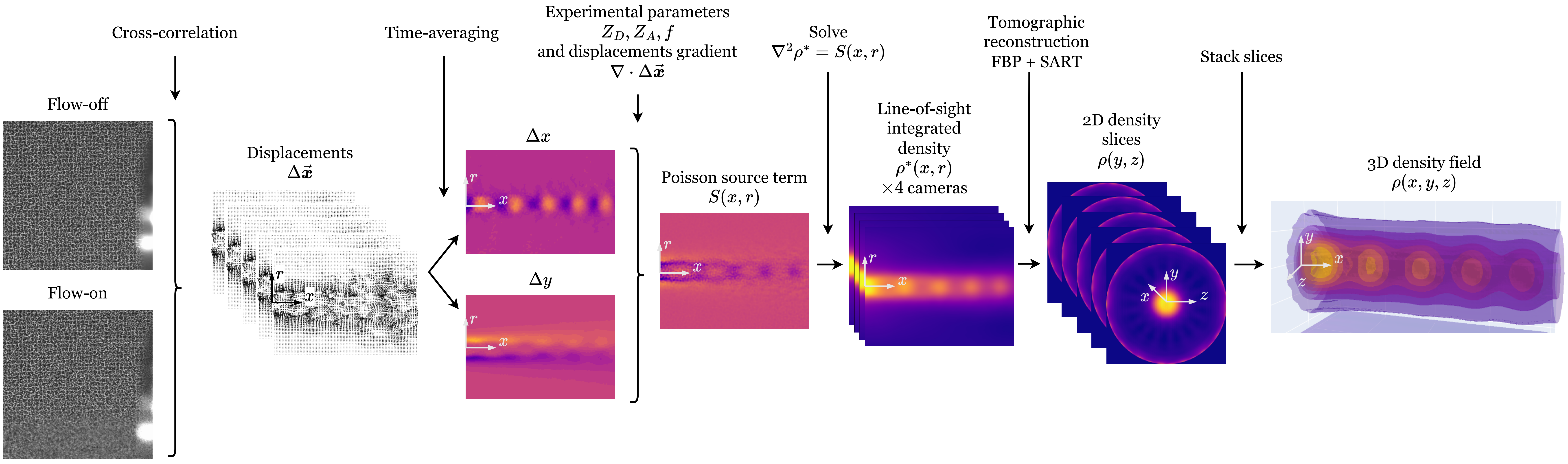
Experimental Setup

The experimental setup consists of the ASCENT test rig (housing the overexpanded aluminium nozzle), and a circular camera-background array. The circular array consists of four camera-background pairs, placed in a 90° arc at equal 30° intervals in a plane orthogonal to the nozzle x-axis. The cameras and backgrounds were placed at approx. 1.0 m and 0.9 m from the nozzle axis, respectively. Measurements were conducted at three NPR values (12, 22 and 26), corresponding to distinctly different flow regimes.

[1] Raffel, M. (2015). "Background-oriented schlieren (BOS) techniques". In: *Experiments in Fluids* 56.3. DOI: 10.1007/s00348-015-1927-5

[2] Bron, J. A., W. J. Baars and F. F. J. Schrijer (2023). "Density Field Reconstruction of an Overexpanded Supersonic Jet using Tomographic Background-Oriented Schlieren". DOI: 10.48550/arXiv.2311.10332

Figure 1. Three-dimensional density field reconstruction framework (see paper by J. A. Bron et al. [2] for more details)



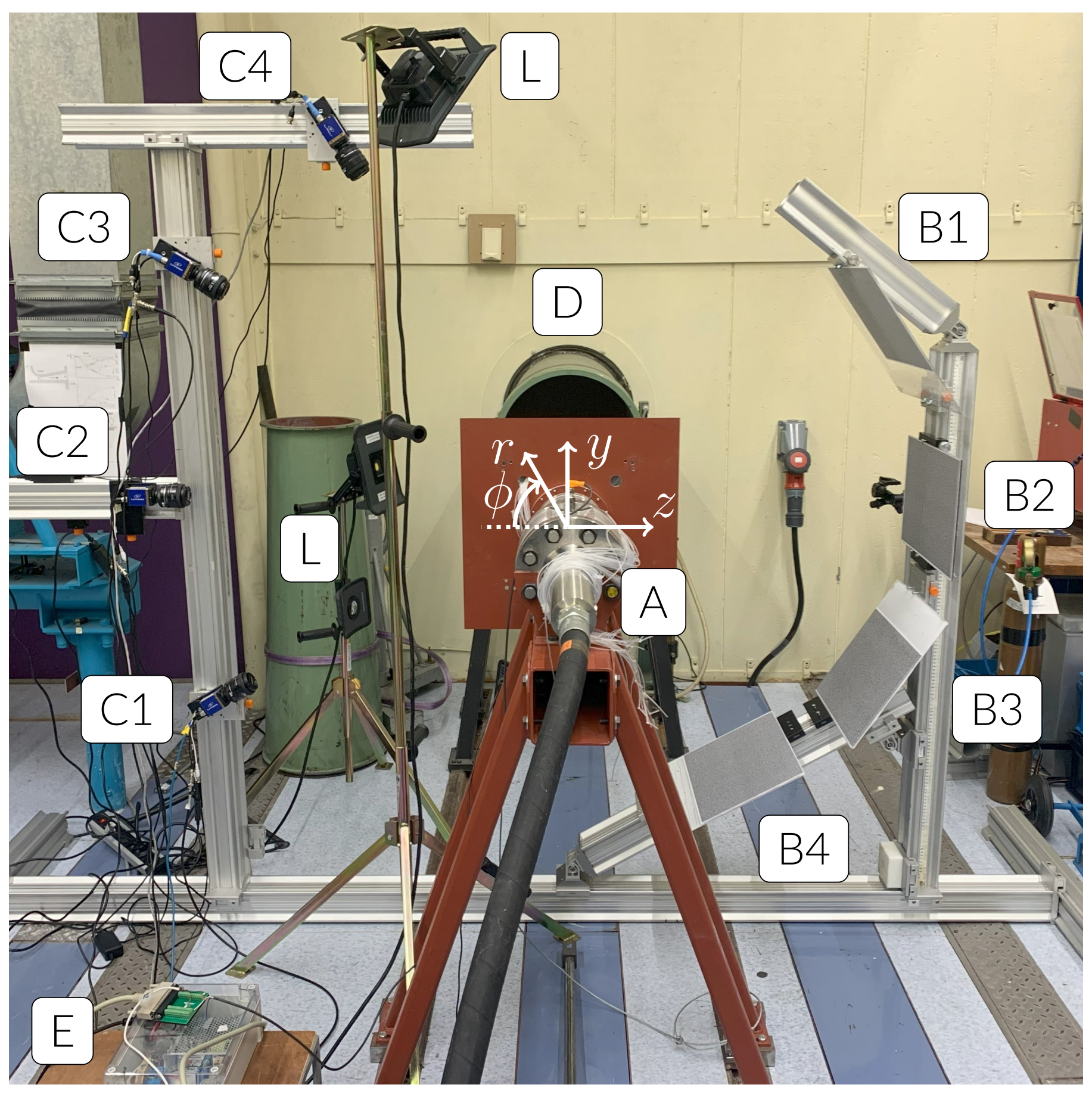


Figure 2. Back view of the experimental setup. Legend: A - ASCENT test rig, B - backgrounds, C - cameras, D - diffuser, E - data acquisition control box, L - LED lamps.

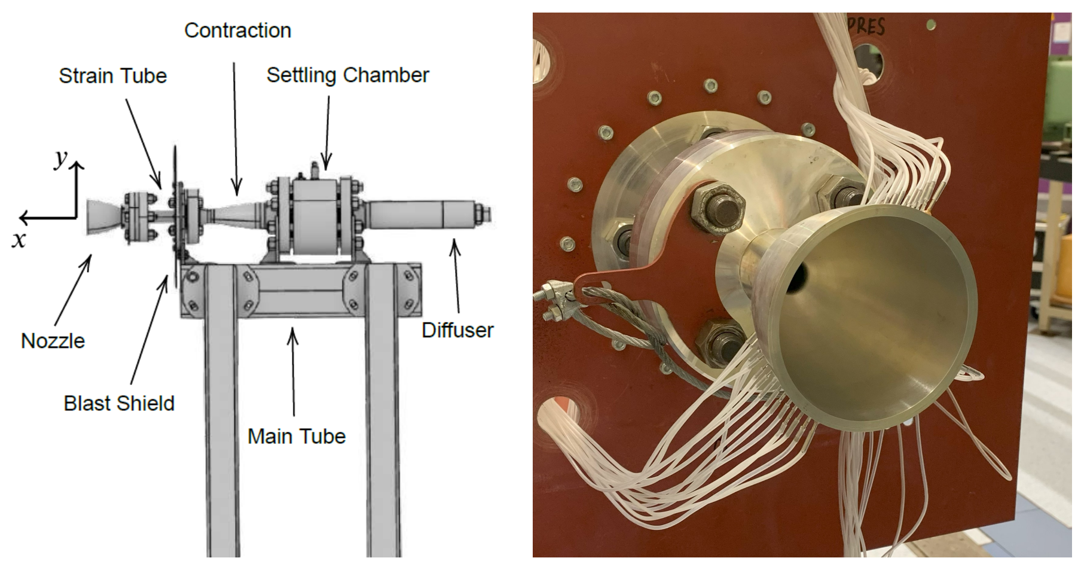


Figure 3. ASCENT test rig (left) and aluminium nozzle (right).

Results

An arbitrary, instantaneous displacement field as captured by one of the cameras is shown in fig. 5. Using these fields, the three-dimensional time-averaged density field for the NPR 12, 22 and 26 cases was reconstructed. The two-dimensional (x, z) planes of time-averaged density, at $y = 0$, are shown in fig. 6. Shock diamonds are clearly visible, and the shock spacing is found to be $0.4D$ and $0.25D$ for NPR 12 and 22, respectively. Fig. 4 shows three-dimensional density iso-surfaces for the NPR 12 case.

Due to the few number of projections used, tomographic reconstruction artefacts are visible. Also, the reconstruction has a relatively low spatial resolution and is unable to resolve sharp shock fronts. Despite these limitations, the three-dimensional shock structure is clearly visible and the spacing can accurately be extracted.

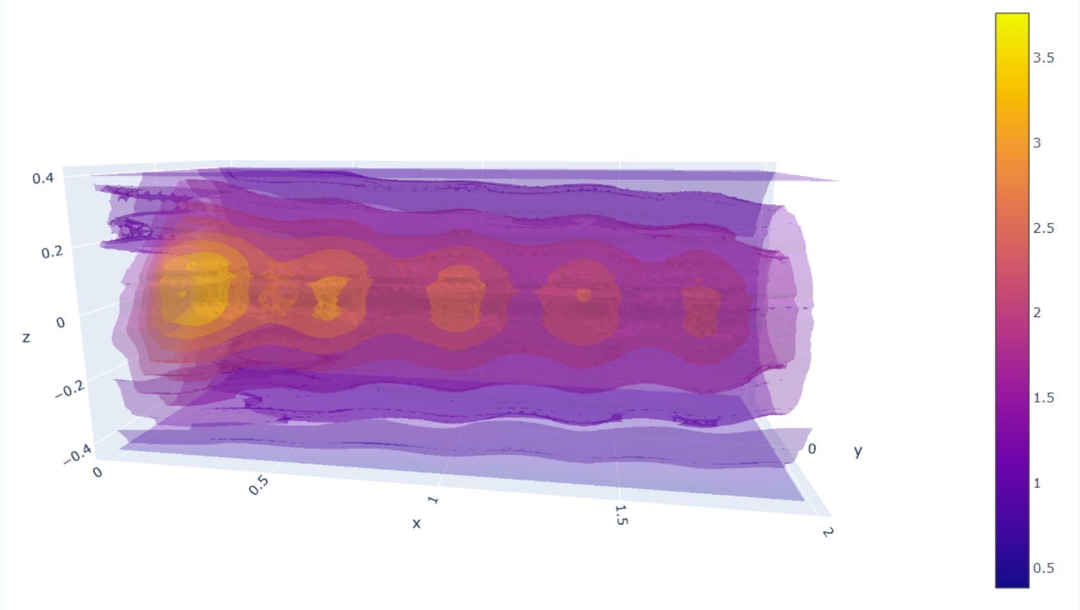


Figure 4. 3D normalized density field ρ/ρ_0 iso-surfaces for NPR 12.

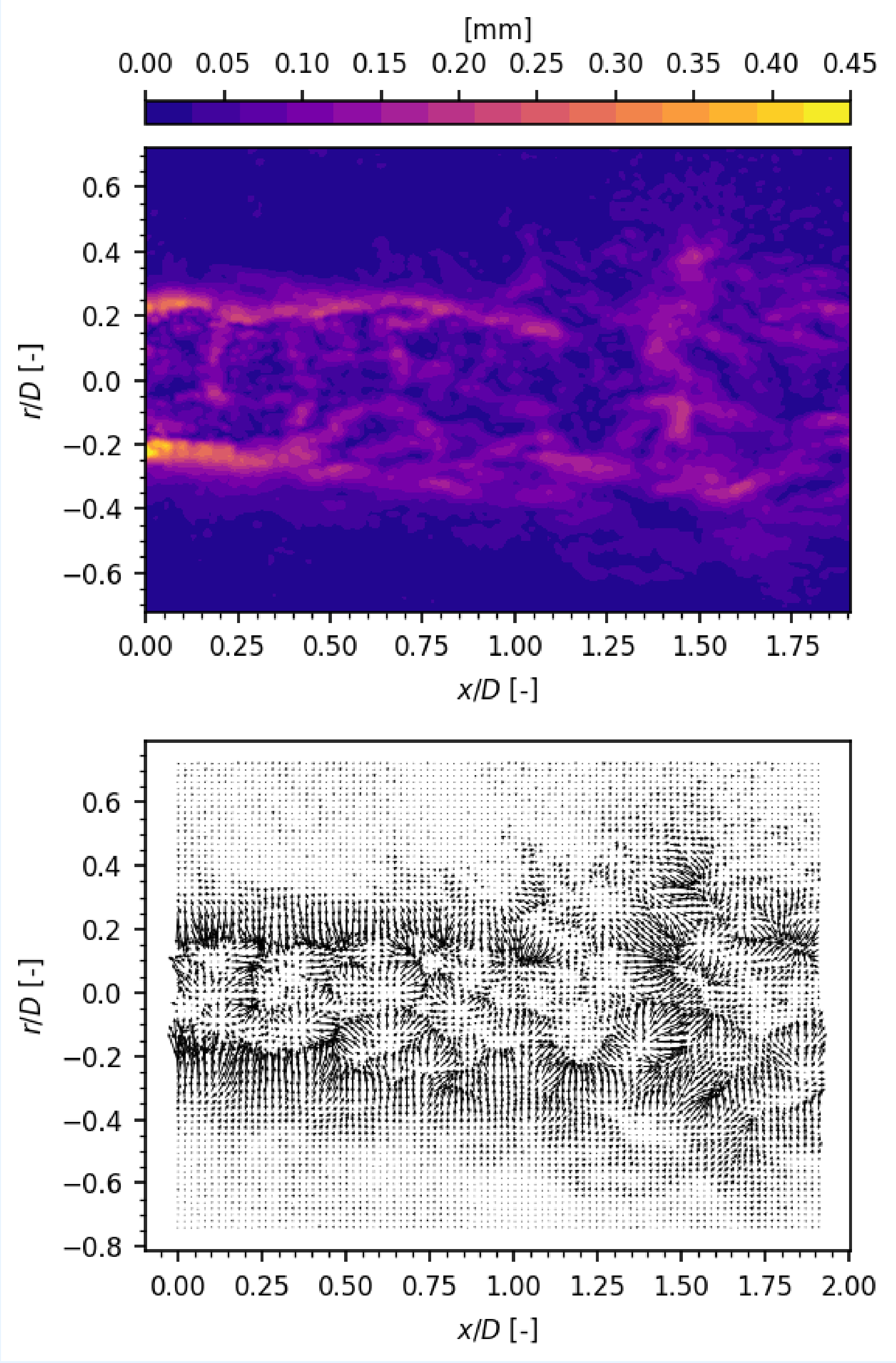


Figure 5. Instantaneous displacement magnitude (top) and displacement vector field (bottom) for an arbitrary projection snapshot at NPR 22.

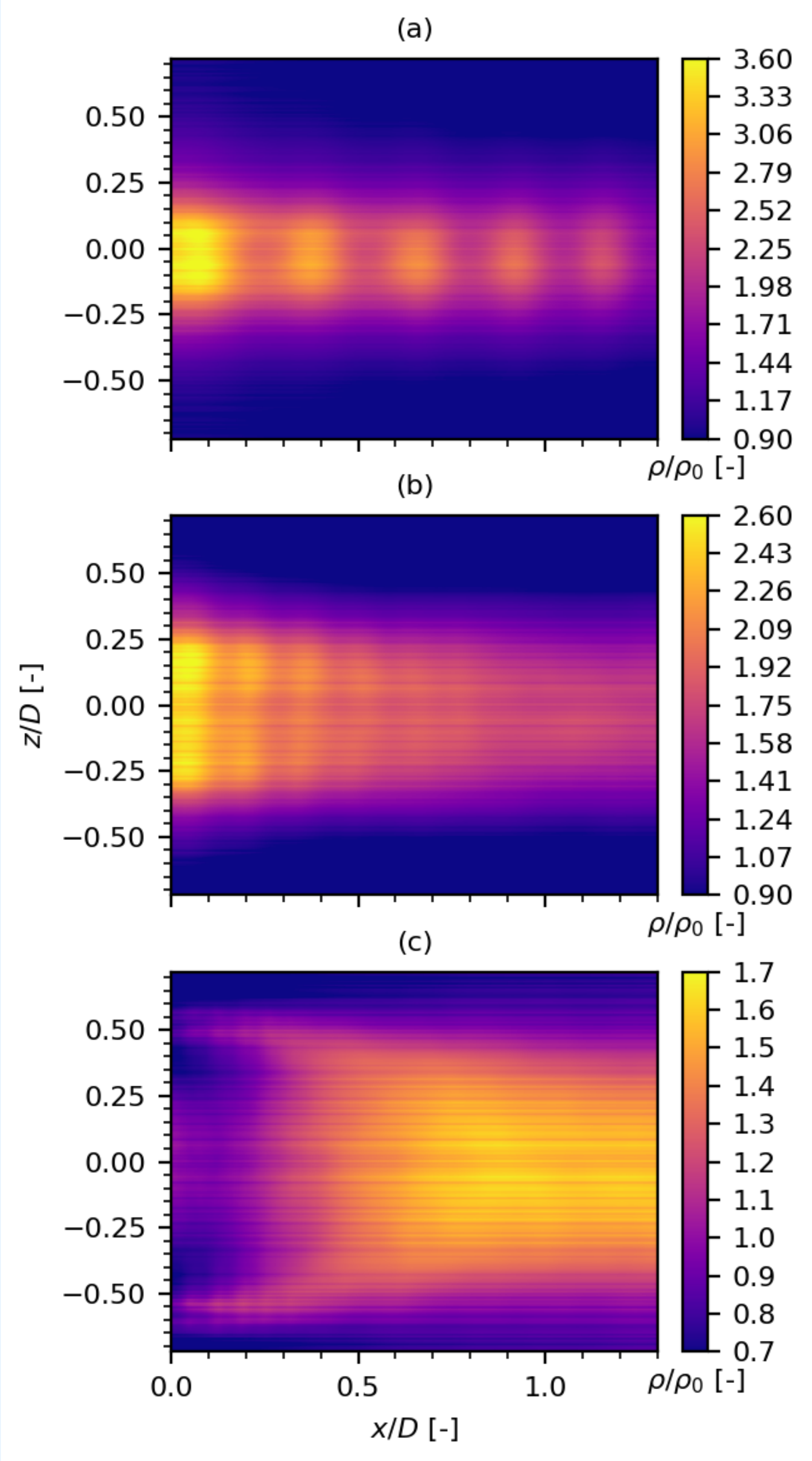


Figure 6. $x/D - z/D$ plane at $y/D = 0$ of the normalized density field for NPR 12 (a), 22 (b) and 26 (c). Note: $D = 90$ mm.

https://github.com/joabron/   Honours Programme Bachelor of the Faculty of Aerospace Engineering — Symposium 2023