

# High-resolution velocity field in the first Mach disk region of an overexpanded supersonic jet

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## ABSTRACT

Overexpanded supersonic jets, occurring when the nozzle exit pressure falls below ambient, are characterised by a complex shock-cell structure including oblique shocks, reflected shocks and, under certain conditions, Mach disks followed by subsonic pockets. These flow features are of critical importance for launch vehicle design as they may impact thermal and acoustic conditions on the launchpad, structural and thermal loads on the afterbody as well as plume afterburning and signature. Despite this relevance, well-resolved experimental velocity datasets in overexpanded jets remain scarce, limiting the validation of compressible flow solvers in this regime. This work presents high-resolution planar Particle Image Velocimetry (PIV) measurements performed in the first shock cell of a large Reynolds number overexpanded free heated air jet at approximately Mach 3, produced by the large-scale ADIJE facility at ONERA, operating at generating pressure of 21 bar and temperature of 670 K. SiO<sub>2</sub> seeding particles with an estimated relaxation time below 0.7  $\mu$ s ensure reliable tracking of the strong velocity gradients across the shock structure, and a high-magnification optical setup provides a vector spacing of 22  $\mu$ m. Experimental velocity fields are compared to a Large Eddy Simulation (LES), showing an overall excellent agreement between the two datasets. Two main findings are reported. First, a shock-tracking procedure based on instantaneous velocity probability density functions reveals that the Mach disk oscillates axially with a peak-to-peak amplitude of approximately 1.5 mm. Computing a conditional average in the shock reference frame reduces the standard deviation peak at the Mach disk location by approximately 100 m/s, representing 40% of the standard deviation value computed in the fixed (camera) reference frame. The shock displacement is therefore identified as a significant though not dominant contribution to the velocity fluctuations in that region, the remainder being attributed to turbulence and measurement noise. Second, no negative axial velocity, i.e. recirculating flow, is measured anywhere in the dataset, with the minimum average axial velocity consistently near 200 m/s, in contrast to the corresponding LES which predicts a drop down to -100m/s on the jet axis immediately downstream of the Mach disk. The consistency of the PIV data across the complete dataset, combined with the limited confidence in the LES prediction in the subsonic pocket region, establishes these measurements as a reliable reference dataset for the validation of compressible flow solvers applied to overexpanded supersonic jets.

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## 1. Introduction

Convergent-divergent nozzles are widely used in propulsion systems, in particular for launch vehicles, to accelerate the exhaust gas to supersonic velocity and generate thrust. The aerodynamic behaviour of the jet at the nozzle exit is governed by the ratio between the static pressure at the nozzle outlet and the ambient pressure. When this ratio equals unity the jet is said to be adapted, but this condition can rarely be maintained throughout a flight envelope. At low altitude — and in particular during lift-off — the nozzle usually operates in an overexpanded regime, where the exit pressure falls below ambient. This regime can generate unsteady loads on the nozzle and the afterbody, making it a critical consideration for the design and safety of launch vehicles [Crist et al. (1966); Simmons (2000); Wang & Guidos (2009); Wernet et al. (2021)].

The overexpanded jet is characterised by a rich shock structure that develops downstream of the nozzle exit. Oblique incident shocks form at the nozzle lip and converge toward the jet axis, where they interact to form a strong normal shock known as the Mach disk [Crist et al. (1966); Reijasse et al. (2002); Ahn et al. (2003); Addy (2012); Langenais et al. (2019)]. This interaction occurs at a triple point from which a reflected shock and a slip line also emanate. Behind the Mach disk, the flow decelerates abruptly to subsonic velocities, forming a bounded subsonic pocket delimited by the slip line and the reflected shock [Crist et al. (1966); Addy (2012); Langenais et al. (2019)]. Downstream of the Mach disk, a compression fan reconverges the flow toward the axis, feeding successive shock cells whose strength decreases with distance as turbulent mixing dissipates the shock-cell pattern [Reijasse et al. (2002); Addy (2012)].

Within the subsonic pocket, numerical simulations have reported the existence of a reverse flow region on the jet axis, predominantly in underexpanded configurations [Skovorodko (2011); Kashkovsky et al. (2024); Kudryavtsev et al. (2024)]. The physical origin of this recirculation was discussed by Skovorodko [Skovorodko (2011)], and its existence was later confirmed through three-dimensional Navier–Stokes and DSMC simulations, ruling out an axisymmetric numerical artefact [Kashkovsky et al. (2024)]. Importantly, Kudryavtsev et al. [Kudryavtsev et al. (2024)] demonstrated that this reverse flow is Reynolds-number-dependent: it is present at low Reynolds numbers but vanishes beyond a certain threshold. This is consistent with the experimental findings of Edgington-Mitchell et al. [Edgington-Mitchell et al. (2014)], who reported no recirculation in an underexpanded jet at a Reynolds number comparable to that of the ADIJE facility.

For overexpanded configurations, the situation is less well documented. Two studies report recirculating flow downstream of the Mach disk, but both involve geometries that differ substantially from the free-plume shock structure of a standard overexpanded jet. Martelli et al. [Martelli et al. (2020)] address the internal nozzle flow in a free shock separation (FSS) regime, in which a conical separation shock merges into the Mach disk inside the nozzle. Reijasse et al. [Reijasse et al. (2002)] experimentally confirmed a recirculation bubble by two-component LDV measurements

in a thrust-optimized contoured (TOC) nozzle, but in that case the recirculation is driven by an internal focusing shock that interferes with the overexpansion shock to form a cap-shock pattern. Neither configuration is representative of the oblique shock–Mach disk interaction that develops in the free plume of a standard overexpanded jet, and no experimental evidence for or against axial recirculation appears to be available for such a configuration at high Reynolds number.

Despite the practical importance of overexpanded jets, quantitative experimental data on their internal flow structure remain scarce. Most available studies have relied on optical visualisation techniques — schlieren and shadowgraphy — to characterise the shock topology of the exhaust plume [Reijasse et al. (2002)], or on wall pressure measurements to document the separation and side-load dynamics inside the nozzle [Hadjadj & Onofri (2009); Martelli et al. (2020)]. Direct velocity measurements within the jet plume are far less common, and have been attempted in only a limited number of overexpanded configurations [Ahn et al. (2003); Ramsey et al. (2012)]. The hostile environment — strong density gradients, particle lag across shocks, intense acoustic emissions, and the need for homogeneous seeding in high-speed flows — makes accurate velocity measurements particularly challenging. As a result, well-resolved, quantitative velocity datasets covering the full first shock cell, including the Mach disk region and the subsonic pocket downstream, remain essentially unavailable in the literature.

Such datasets are however needed to support the development and validation of compressible flow solvers. Numerical simulations of overexpanded nozzle flows, whether based on Reynolds-Averaged Navier–Stokes (RANS) or higher-fidelity approaches such as Large-Eddy Simulation (LES) and Detached-Eddy Simulation (DES), are routinely employed in the design process of propulsive nozzles [Martelli et al. (2020)]. Yet their predictive accuracy in shock-laden, separated flows is difficult to assess without spatially resolved experimental reference data. Velocity fields are particularly valuable in this respect, as they provide a direct and comprehensive picture of the flow physics — shock positions, post-shock velocity distribution including the possible presence of reverse flow in the subsonic pocket, extent of the subsonic pocket, jet spreading — that pressure or density measurements alone cannot supply. Highly resolved PIV measurements in an overexpanded jet would thus constitute a reference dataset of broad utility for the CFD community working on compressible jet flows [Langenais et al. (2019); Wernet et al. (2021); Troyes & Vuillot (2022); Langenais et al. (2023)].

The present work addresses this gap by reporting planar PIV measurements in a round, free overexpanded air jet produced by the large-scale ADIJE facility at ONERA. The overexpanded jet with a design Mach number of 3 presents a well-defined Mach disk in the first shock cell. Velocity fields were measured on a symmetry plane covering the first shock cell, with particular attention to the Mach disk region and the associated subsonic pocket.

## 2. Experimental and numerical setup

### 2.1. ADIJE facility

The experiments were performed at the ADIJE facility at ONERA. The facility consists of an instrumented pipe fitted with a de Laval nozzle at its exit, as shown in Figure 1, with a throat diameter of 19.4 mm and an exit diameter of  $D = 40$  mm at ambient temperature; thermal expansion of the nozzle walls under hot flow conditions may result in slightly larger effective dimensions during operation. The nozzle is supplied with a continuous flow of hot air at a total temperature of  $T_i = 670$  K and a total pressure of  $p_i = 21$  bar.

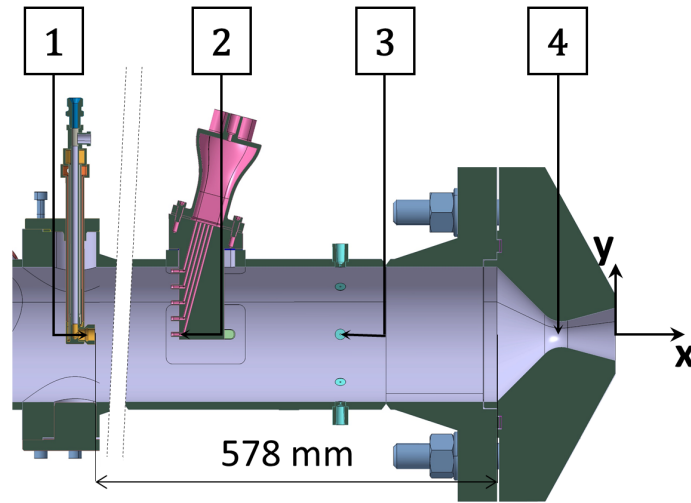


**Figure 1.** Schematic overview of the ADIJE facility: (1) seeding injection outlet, (2) K-type thermocouple comb, (3) static pressure sensors, (4) de Laval nozzle with throat diameter 19.4 mm and exit diameter 40 mm.

At the nozzle exit, the design Mach number is 3 and the corresponding ideally expanded Mach number is 2.6. The pressure ratio  $p_j/p_\infty \approx 0.6$ , the exit velocity  $u_j \approx 900$  m/s, and the Reynolds number is estimated at  $2 \times 10^6$ . Under these conditions, several successive shock cells are clearly visible in the exhaust plume. Once the experiment is running, the noise levels make it impossible to stay in the facility room, and all measurements are therefore conducted remotely.

Eight static pressure sensors are distributed around the pipe wall. A comb of five K-type thermocouples, inserted radially across the flow, provides a temperature profile along the pipe radius. During standard operation, pressure and temperature are recorded continuously at 0.5 Hz, increasing to 10 Hz during optical measurements. The inlet generating conditions are defined as a single value: the time average over the 30-second acquisition window of the spatial average across the five thermocouple readings for temperature, and across the eight wall pressure sensor readings for pressure. In the pipe section where measurements are taken, the flow velocity is sufficiently low that static and total pressure can be considered equal. A total pressure sensor located further

upstream reads 1.1% above the average of the eight wall sensors; the latter are preferred as they are located closer to the nozzle and provide a more robust estimate by averaging over multiple measurement points rather than relying on a single location. The maximum temperature variation across the radial profile is 0.5% and the radial variation of static pressure is less than 0.2%, confirming the uniformity of the inlet flow.

The mass flow rate is computed by two independent methods: from upstream temperature and pressure measurements across a calibrated throat, and directly from the generating conditions. The two estimates agree to within 1%. The operating conditions recorded during the PIV measurements are summarised in Table 1, together with the conditions used for the corresponding LES computation.

| Reference | Temperature [K] | Pressure [bar]   | Mass flow rate [kg/s] |
|-----------|-----------------|------------------|-----------------------|
| PIV #1    | $666.7 \pm 1.6$ | $21.15 \pm 0.03$ | $0.972 \pm 0.001$     |
| PIV #2    | $669.9 \pm 1.7$ | $20.90 \pm 0.02$ | $0.958 \pm 0.001$     |
| LES       | 670             | 21               | 0.967                 |

**Table 1.** Operating conditions during the PIV measurements and the corresponding LES computation. Average measured quantities are given with their standard-deviation during the PIV acquisition, these values are not uncertainties.

## 2.2. PIV setup

Seeding particles of  $\text{SiO}_2$  (nominal diameter  $\approx 200$  nm, density  $2.3 \text{ g/cm}^3$ ) are suspended in air using a custom-made high-pressure cyclone device and injected upstream of the nozzle throat (pipe labelled “1” in Fig. 1), ensuring homogeneous seeding throughout the jet. To limit the formation of particle aggregates, hydrophobic particles are used. Additionally, the particles are stored at 400 K in an oven overnight prior to the experiment to remove any residual humidity, and sieved upon loading into the seeding device. Their relaxation time, estimated below  $0.7 \mu\text{s}$ , is short enough to capture the strong velocity gradients encountered across the shock structure as accurately as possible. A frequency-doubled dual-cavity Nd:YAG laser (Quantel CFR) operating at 15 Hz and delivering 120 mJ per pulse generates a laser sheet illuminating the seeded flow. Scattered light is collected at  $90^\circ$  to the sheet by an sCMOS camera (LaVision) equipped with a 300 mm focal-length  $f/4.5$  lens and extension tubes, providing a field of view of  $23 \text{ mm} \times 27 \text{ mm}$  at a magnification of  $11 \mu\text{m/pixel}$ . The inter-pulse delay is set and measured to 144 ns, appropriate for the velocity range and spatial resolution of the system.

Velocity fields are computed from cross-correlation of image pairs using LaVision Davis 10, with a final interrogation window of  $12 \times 12$  pixels at 75% overlap, yielding a vector spacing of  $22 \mu\text{m}$ . Measurements are performed with two successive fields of view covering preferentially either side of the Mach disk (denoted PIV#1 and PIV#2). At each position, 450 instantaneous velocity fields

are recorded, providing statistically converged average fields and reliable estimates of the local standard deviation. The two fields of view are subsequently merged to reconstruct the full topology of the first shock cell. The combination of sub-micron particles, superior particle relaxation time, and high spatial resolution enables accurate measurement of the steep velocity gradients associated with the Mach disk and the surrounding shock structure.

### 2.3. Large-Eddy Simulation

The experimental results are compared to a Large-Eddy Simulation of the ADIJE jet performed with the code CEDRE [Refloch et al. (2011)] at the same generating conditions as the experiment (see Table 1). The simulation is carried out by solving the filtered compressible Navier-Stokes equations on an unstructured mesh of approximately 128 million cells. The specific heat of air is defined by a 7th order polynomial. Turbulence is modelled using the Smagorinsky subgrid-scale model with a constant  $C_s = 0.1$ . The fluxes are calculated with a Harten-Lax-van Leer-Contact (HLLC) scheme. Second-order schemes are used for both spatial discretisation (multi-slope MUSCL method) and time integration (Crank-Nicolson implicit scheme), with a time step of  $\Delta t = 2 \times 10^{-7}$  s. Statistics are accumulated over a physical time of 24 ms, i.e.  $\approx 540D/u_j$ . Synthetic momentum source terms are inserted at the nozzle wall to favor the turbulence development in the boundary layer, consequently in the jet mixing layer downstream as required to properly simulate a supersonic jet [Langenais et al. (2019)]. However, no turbulence is injected in the core of the flow and consequently inside the potential core, which constitutes a modelling limitation when comparing standard deviation fields with the experimental data, as discussed in Section 3.2.

## 3. Results

### 3.1. Shock structure and mean flow topology

The average (top panel) and standard deviation (bottom panel) fields of axial velocity obtained from PIV and LES are presented in Figure 2a, each split horizontally between PIV (top half) and LES (bottom half). Fig. 2b shows axial profiles of  $\mu_{u_x}$  and  $\sigma_{u_x}$  along the jet axis ( $y = 0$  mm). The two PIV acquisitions overlap perfectly in their common region, demonstrating the reproducibility of both the measurements and the facility operating conditions.

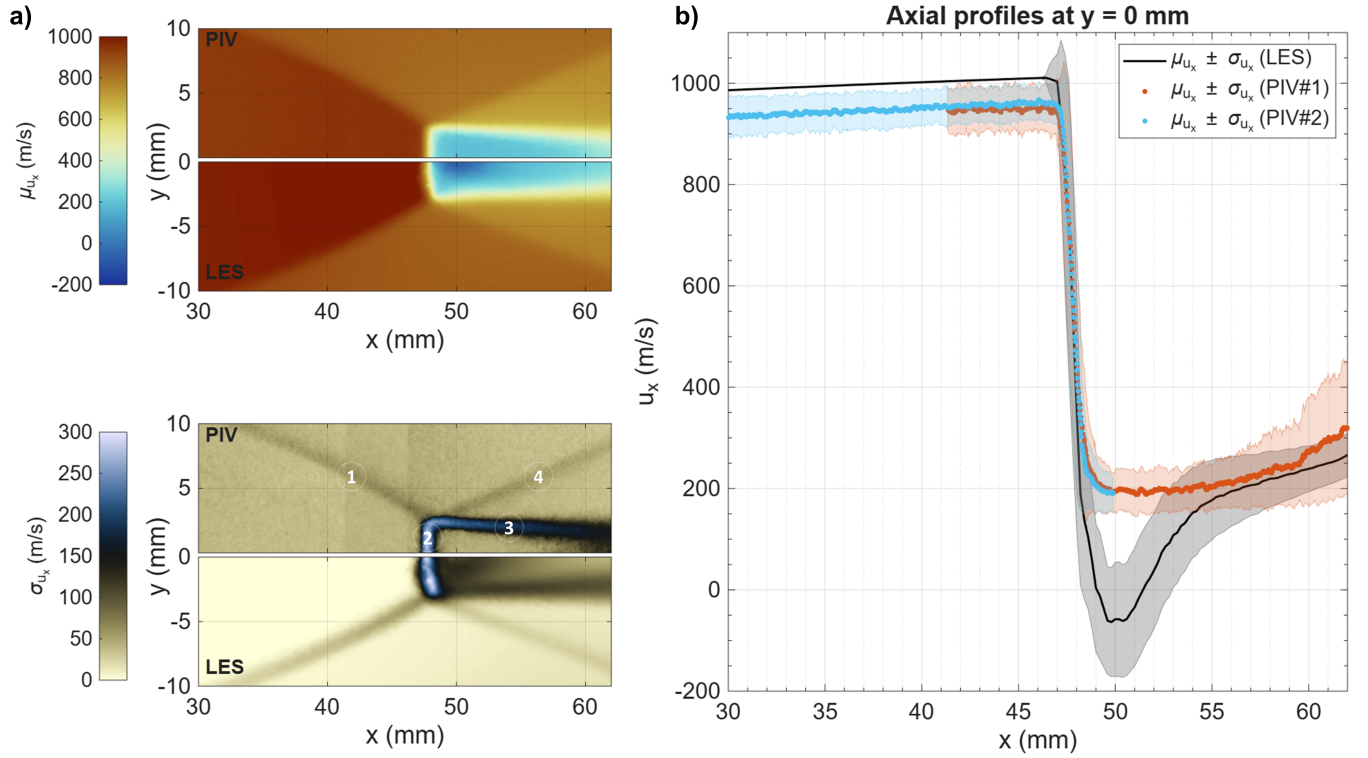


**Figure 2.** a) Average field  $\mu_{u_x}$  (top panel) and standard deviation field  $\sigma_{u_x}$  (bottom panel), each with PIV in the upper half and LES in the lower half with (1) incident shock, (2) Mach disk, (3) slip line, and (4) reflected shock. b) Axial profiles of  $\mu_{u_x}$  and  $\sigma_{u_x}$  along  $y = 0$  mm for PIV#1, PIV#2, and LES.

The PIV average field clearly resolves the main features of the first shock cell: the supersonic core upstream of the Mach disk, where the mean axial velocity  $\mu_{u_x}$  reaches approximately 1000 m/s, the sharp velocity drop across the Mach disk, and the subsonic pocket downstream where the flow decelerates to a minimum of approximately 200 m/s. The standard deviation  $\sigma_{u_x}$  field reveals the incident shocks originating from the nozzle lip, the reflected shocks, and the slip line as regions of elevated  $\sigma_{u_x}$ , due to their spatial unsteadiness.

Comparison with the LES reveals two notable discrepancies. First, the LES predicts a slightly higher upstream velocity, approximately 60 m/s above the PIV measurement. The origin of this discrepancy remains unclear and is currently under investigation. Limited particle slip in the jet potential core and heat losses at the nozzle walls, not considered in the numerical simulation, are possible explanations. Whatever its origin, the gap between experimental and numerical velocity remains below 7%. Second, and more significantly, the LES predicts near-zero or slightly negative  $\mu_{u_x}$  in the subsonic pocket, whereas PIV consistently measures a minimum of approximately 200 m/s. It should be noted that the confidence in the LES prediction of the minimum velocity in the subsonic pocket is limited, as this region is particularly sensitive to modelling choices such as inlet boundary conditions, numerical schemes, and turbulence closure. The standard deviation fields exhibit a further discrepancy: the LES  $\sigma_{u_x}$  is near zero throughout the supersonic core up-

stream of the Mach disk, while PIV records approximately 50 m/s in the same region. The origin of this difference is examined in Section 3.2.

### 3.2. Mach disk dynamics and position tracking

Figure 3a presents the average and standard deviation fields of axial velocity in the Mach disk vicinity, and Fig. 3b shows the probability density functions (pdf) of the instantaneous axial velocity  $u_x$  computed at nine axial locations across the shock transition. At locations far upstream of the Mach disk (location 1), where the standard deviation is low, the distribution is narrow and peaked around 950–1000 m/s, which is consistent with a nearly steady supersonic flow only occasionally disturbed by the passing shock front. At locations in the transition region (locations 3 to 7), where the average velocity is approximately 600 m/s and the standard deviation is maximum, the distribution spans the full range from 100 m/s to 1000 m/s, which is the signature of intermittent shock passages through the measurement point rather than broadband turbulent fluctuations. At locations far downstream in the subsonic pocket (location 9), the distribution is narrow and peaked around 200 m/s, indicating a relatively steady subsonic flow where the influence of shock displacement is negligible. It thus appears that the Mach disk location oscillates along the axial direction.

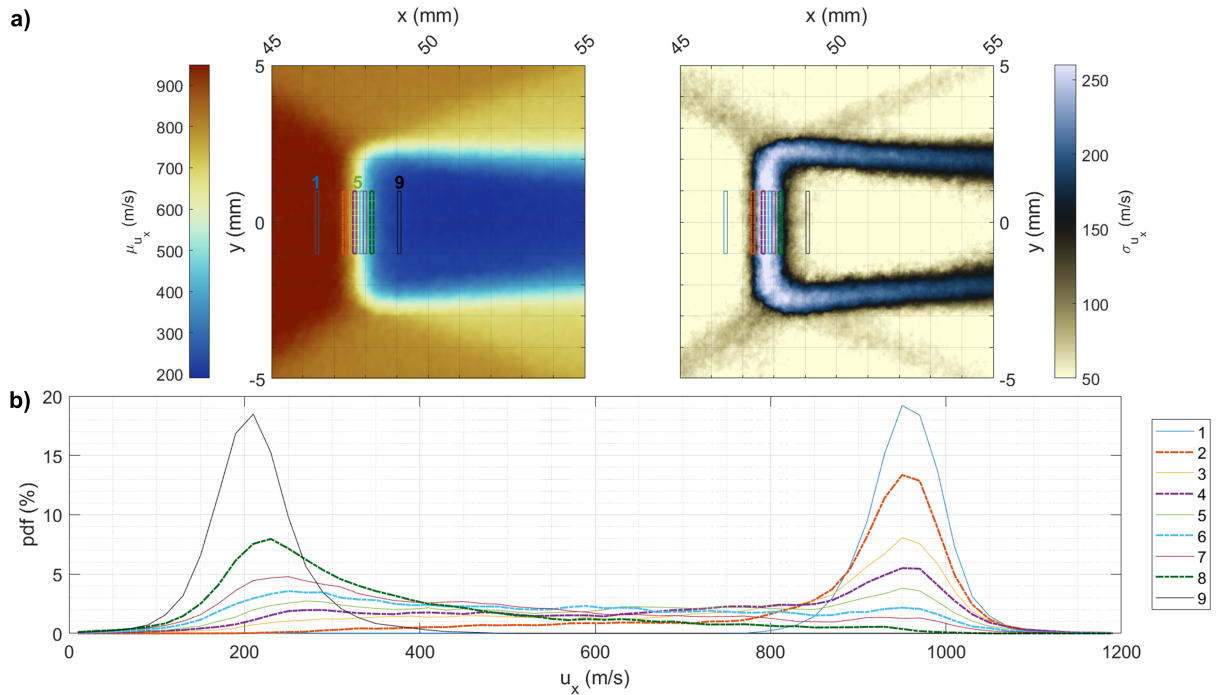


**Figure 3.** a) Left: average field  $\mu_{u_x}$  in the Mach disk vicinity with the nine axial locations indicated. Right: standard deviation field  $\sigma_{u_x}$ . b) Probability density functions of instantaneous  $u_x$  at each of the nine axial locations.

To quantify the shock motion, a statistical procedure is applied to each instantaneous field, as

illustrated in Figure 4. Figure 4a shows an example instantaneous  $u_x$  field, where the sharp transition between the supersonic and subsonic regions is clearly visible. Figure 4b displays the row-by-row  $u_x$  profile with a fine-bin pdf (bin width 20 m/s) computed over a transverse strip  $y \in [-1.5, 1.5]$  mm at each axial location. At this resolution, the progressive shift from the supersonic to the subsonic velocity population across the shock transition is clearly visible. Figure 4c shows the same profile with a coarser bin width of 200 m/s, at which the bimodal character of the distribution is clearly separated into a high-velocity supersonic population and a low-velocity subsonic population. The instantaneous shock position is then defined as the average axial location between two thresholds: the high-speed threshold is the last axial location where the velocity population is predominantly in the 800–1000 m/s bin, and the low-speed threshold is the first axial location where it is predominantly in the 200–400 m/s bin. The wrinkled aspect of the shock in Fig. 4a can be explained by the combined effect of upstream and downstream flow turbulence and PIV post-processing algorithm noise.

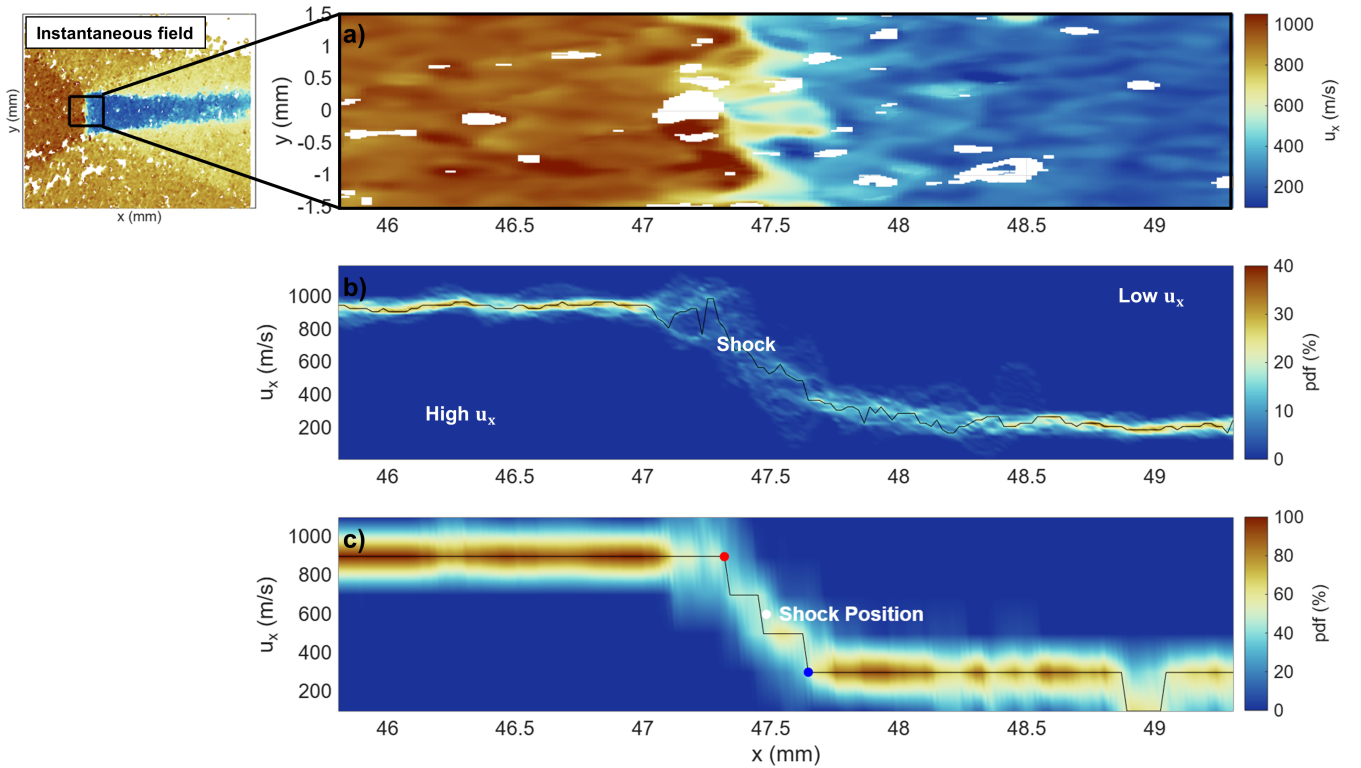


**Figure 4.** Determination of the instantaneous Mach disk position. a) Instantaneous  $u_x$  field in the Mach disk region. b) Row-by-row  $u_x$  profile with fine-bin pdf (bin width 20 m/s). c) Row-by-row  $u_x$  profile with coarse-bin pdf (bin width 200 m/s) Shock position (white) is identified by the iso-distance between red and blue threshold markers. The black line highlights the local maximum of the pdf.

This procedure is applied to all 900 instantaneous fields from both PIV measurement positions (450 fields per position). Fields are retained only if more than 60% of the vectors are valid in the Mach disk area ( $x \in [46, 50]$  mm,  $y \in [-1.5, 1.5]$  mm), reducing the dataset to 580 fields. The temporal

distribution of Mach disk positions computed from these fields is shown in Figure 5. The Mach disk oscillates axially with a peak-to-peak amplitude of approximately 1.5 mm, centred around  $x \approx 47.75$  mm, with an approximately Gaussian distribution.

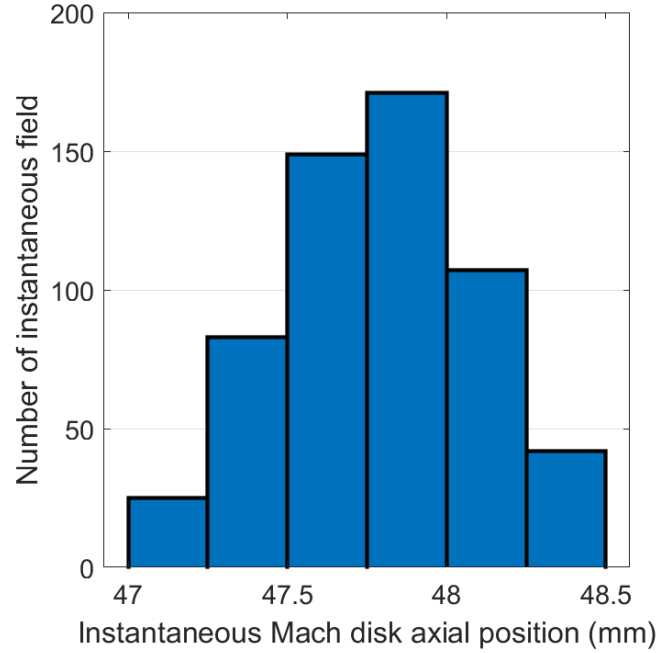


**Figure 5.** Histogram of the instantaneous Mach disk axial position over the 580 selected PIV fields.

Based on the shock positions extracted from each retained field, a conditional average is computed in the shock reference frame and compared to the fixed-frame average and a representative instantaneous field in Figure 6. Fig. 6a shows axial profiles of  $\mu_{u_x}$  and Fig. 6b shows the corresponding  $\sigma_{u_x}$  profiles, both for the camera and shock reference frames, together with LES profiles extracted at  $z = 0, 1$  and 2 mm, where  $z$  denotes the out-of-plane coordinate. The shock-tracking metric is validated by the fact that the conditional average produces a sharper velocity transition than the fixed-frame average without introducing spatial distortion of the field, confirming that the metric correctly identifies the instantaneous shock position.

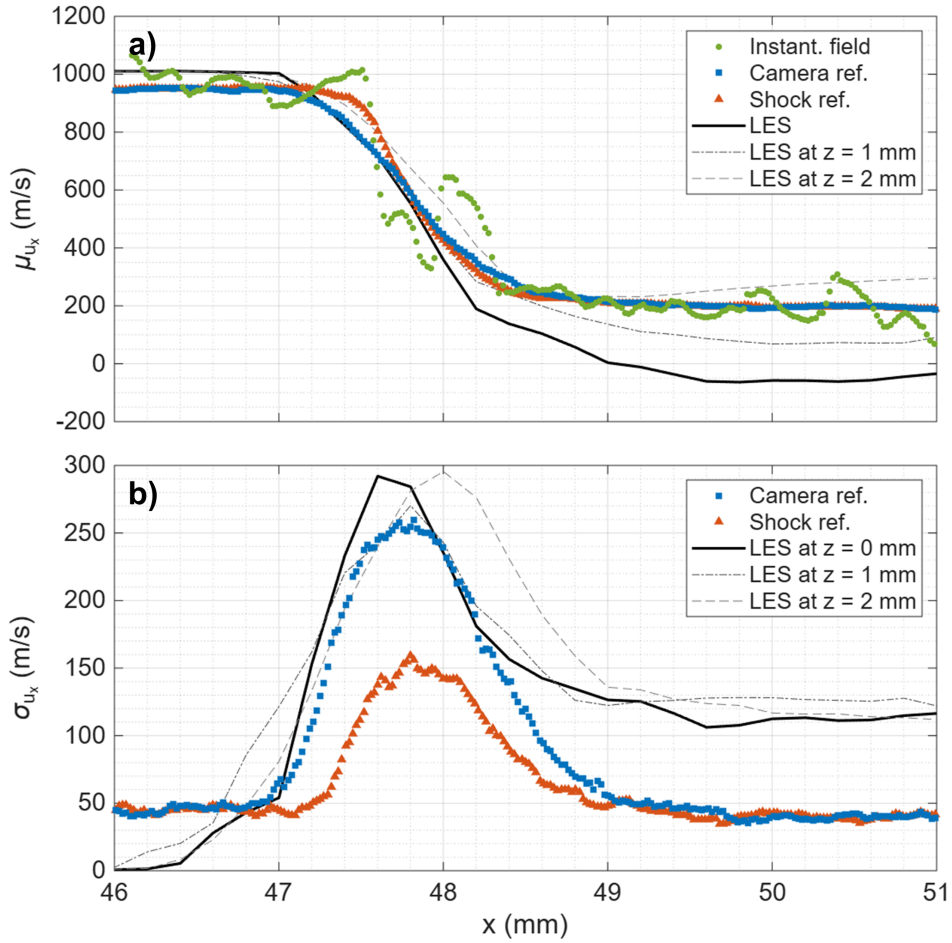


**Figure 6.** a) Axial profiles of  $\mu_{u_x}$  at  $y = 0$  mm for an instantaneous field, camera-reference average, shock-reference average, and LES at  $z = 0, 1$  and  $2$  mm. b) Corresponding  $\sigma_{u_x}$  profiles.

In the standard deviation profiles, switching from the camera to the shock reference frame reduces the  $\sigma_{u_x}$  peak at the Mach disk location, from approximately 250 m/s to 150 m/s. This reduction of approximately 40% of the camera-frame peak identifies shock displacement as a significant, though not dominant, contribution to the fixed-frame standard deviation peak. The remaining 60% is attributable to other sources, including locally enhanced turbulence in the shock interaction region, turbulence developing within the nozzle that is not represented in the LES inlet boundary conditions, and PIV measurement noise. The residual standard deviation of approximately 40–50 m/s observed upstream of the shock in both reference frames, as well as in the subsonic pocket from  $x \approx 49.2$  mm onward, reflects these same contributions in the absence of shock motion influence.

The second main finding of this study concerns the minimum axial velocity in the subsonic pocket. No negative  $u_x$  is measured anywhere in the dataset — neither in any of the 900 instantaneous fields nor in the shock-referential conditional average — with the minimum  $\mu_{u_x}$  consistently near

200 m/s. This stands in contrast to the LES predicting approximately  $-100$  m/s at  $z = 0$ .

The existence of a reverse flow or recirculation zone on the axis downstream of the Mach disk has been reported in the literature, but most of this evidence comes from numerical simulations of highly underexpanded jets in rarefied conditions. Skovorodko [Skovorodko (2011)] discussed the physical origin of this recirculation zone in underexpanded configurations, and Kashkovsky et al. [Kashkovsky et al. (2024)] confirmed its existence in three-dimensional Navier–Stokes and DSMC simulations, ruling out an axisymmetric numerical artefact. Importantly, Kudryavtsev et al. [Kudryavtsev et al. (2024)] further showed that this reverse flow is Reynolds-number-dependent: it appears at low Reynolds numbers and vanishes when the Reynolds number exceeds a certain threshold, suggesting that it may not be physically present in the high-Reynolds-number conditions of the ADIJE jet. For overexpanded configurations, two references report recirculation downstream of the Mach disk: Martelli et al. [Martelli et al. (2020)], who address an internal FSS nozzle flow in which a conical separation shock merges into the Mach disk inside the nozzle, and Reijasse et al. [Reijasse et al. (2002)], who experimentally confirmed a recirculation bubble by LDV in a thrust-optimized contoured (TOC) nozzle with an internal focusing shock that merges with the overexpansion shock to form a cap-shock pattern. Both configurations differ substantially from the free-plume shock structure of the ADIJE jet, where neither a conical separation shock nor an internal focusing shock is present, making a direct comparison with the present results inappropriate.

The interpretation of the discrepancy between the PIV measurements and the LES therefore requires care. The radial length of the Mach disk seen by the experimental velocity field is comparable to the length predicted by LES at  $z = 0$ , suggesting that the PIV measurement plane is close to the jet axis and is not substantially offset. Yet the experimental minimum  $\mu_{u_x}$  in the subsonic pocket is consistent with LES profiles extracted at  $z = 1$  to  $2$  mm rather than at  $z = 0$ , pointing toward a possible measurement plane offset of at most approximately 1 mm. These two observations are not fully mutually consistent. Given the Reynolds-number dependence of the reverse flow phenomenon, the difference in flow configuration with respect to the overexpanded case of Martelli et al., the limited confidence in the LES prediction of the minimum velocity in this region — which is sensitive to inlet conditions, numerical schemes, and turbulence modelling — and the consistency of the PIV measurements across all 900 fields and both reference frames, the experimental data constitute a reliable characterisation of the velocity field in the subsonic pocket.

#### 4. Conclusion

High-resolution planar PIV measurements have been performed in the first shock cell of an overexpanded air jet ( $M = 3$ ) produced by the ADIJE facility at ONERA.  $\text{SiO}_2$  seeding particles with a relaxation time below  $0.7 \mu\text{s}$ , combined with a vector spacing of  $22 \mu\text{m}$ , enable accurate resolution

of the velocity gradients across the Mach disk and the surrounding shock structure. Average fields reconstructed from 450 instantaneous fields at two adjacent measurement positions confirm the reproducibility of the measurements and the axisymmetry of the jet.

Two results constitute the main findings of this study. First, a shock-tracking procedure based on instantaneous velocity probability density functions, applied to fields selected on the basis of a validity criterion in the Mach disk area, reveals that the Mach disk oscillates axially with a peak-to-peak amplitude of approximately 1.5 mm. Computing the conditional average in the shock reference frame reduces the standard deviation peak at the Mach disk location by approximately 100 m/s, representing approximately 40% of the camera-frame peak, and identifies shock displacement as a significant though not dominant contribution to the fixed-frame standard deviation. The shock-tracking metric is further validated by the absence of spatial distortion in the conditional average field. The residual standard deviation of approximately 40–50 m/s in both the supersonic core and the subsonic pocket reflects turbulent fluctuations — including nozzle-generated turbulence absent from the LES inlet conditions — and measurement noise.

Second, no negative axial velocity is measured anywhere in the dataset, with the minimum average axial velocity consistently near 200 m/s across all instantaneous fields and in the shock-referential conditional average. This is in contrast to the LES prediction of approximately  $-100$  m/s on the jet axis. While a reverse flow behind the Mach disk has been reported numerically for underexpanded jets [Skovorodko (2011); Kashkovsky et al. (2024)], it has been shown to vanish at high Reynolds numbers [Kudryavtsev et al. (2024)], which is consistent with the absence of negative velocities in the present high-Reynolds-number experiment. For overexpanded configurations, two references report recirculation downstream of the Mach disk: Martelli et al. [Martelli et al. (2020)], who address an internal FSS nozzle flow, and Reijasse et al. [Reijasse et al. (2002)], who experimentally confirmed a recirculation bubble by LDV in a TOC nozzle with a cap-shock pattern. Both configurations differ substantially from the free-plume shock structure of the ADIJE jet, where neither an internal focusing shock nor a conical separation shock is present. The radial length of the Mach disk seen by the experimental velocity field, comparable to the LES one at  $z = 0$ , suggests that the measurement plane is close to the jet axis, with a possible offset of at most approximately 1 mm. Given these elements and the full consistency of the PIV measurements across the complete dataset and both reference frames, these experimental results constitute a reliable and high-quality reference dataset for the validation and improvement of compressible flow solvers applied to overexpanded supersonic jets, for both steady RANS approaches and unsteady methods, noting that the present PIV system does not resolve temporally rapid dynamics, but does provide near-instantaneous snapshots (144 ns inter-frame interval) and their statistical fluctuations.

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