*J. Fluid Mech.* (2023), *vol.* 954, F1, doi:10.1017/jfm.2022.964

JFM FOCUS ON FLUIDS

# The screeching jet, seen from all sides

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(Received 4 November 2022; accepted 15 November 2022)

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Shock-containing supersonic jets undergoing resonance processes are challenging from both a measurement and simulation perspective. These jets are host to a broad range of complex fluid phenomena: intense acoustic waves, turbulence, wavepackets and strong shock waves. Strong shocks present a challenge to both the experimental and numerical researcher. In the paper of Léon *et al.* (*J. Fluid Mech.*, vol. 947, 2022, A36), a novel optical technique based on multi-axis digital holographic interferometry is applied to the study of a highly underexpanded screeching jet, producing density measurements of unprecedented clarity and resolution. Where prior studies have been restricted to extrapolating the three-dimensional field from two-dimensional slices or projections, in this work the authors directly measure the three-dimensional helical structure of the wavepacket associated with jet screech.

**Key words:** shock waves, jet noise, high-speed flow

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## 1. Introduction

When supersonic jets operate away from the design condition of the nozzle, a train of shocks and expansion waves forms in the exhaust plume. Interaction between these waves and a range of wavepacket structures supported by the jet introduce several new sources of high-intensity acoustic radiation (Tam 1995). This shock-associated noise has elements both broadband and discrete in frequency, with the latter being associated with a phenomenon known as screech (Edgington-Mitchell 2019). Though screech derives its name from the high-amplitude and discrete-frequency tone associated with the phenomenon, it was first studied optically, rather than acoustically, in the schlieren visualisations of Powell (1953). Following Powell's seminal work, a range of optical and acoustic techniques were applied to the study of the problem, but it was through the lens of linear stability theory that the first significant advancements on Powell's original theory were obtained (Tam, Seiner & Yu 1986). Alongside these experimental and theoretical approaches, recent years have seen the increasingly successful application of high-fidelity numerical methods to the simulation of jet screech. The most significant advances in

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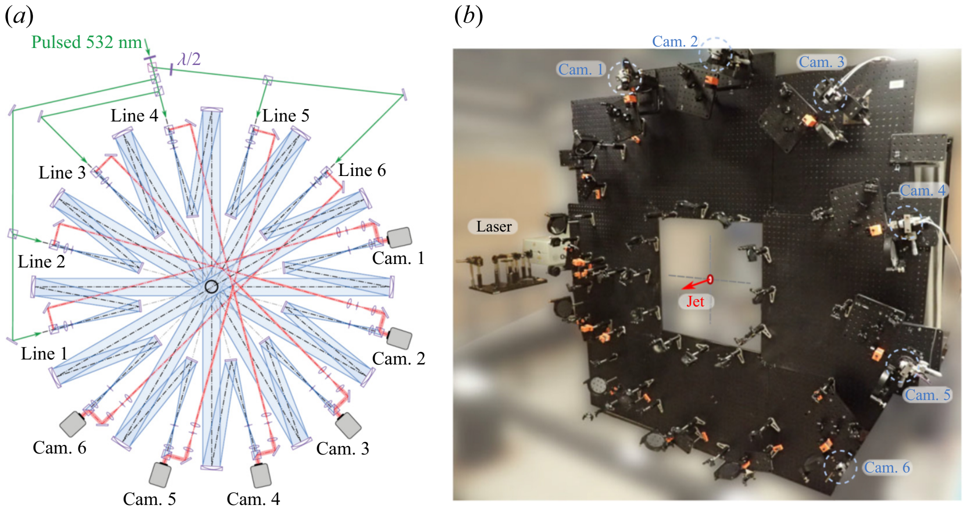

Figure 1. The TDHI set-up from Léon *et al.* (2022): (*a*) schematic; (*b*) photograph. Cam., camera.

our understanding of jet screech have come from pairing the predictions of theoretical models with decompositions of either numerical (Gojon, Bogey & Mihaescu 2018) or experimental (Edgington-Mitchell *et al.* 2021) data.

As the quality of numerical simulations increases, with recent efforts able to reproduce experimentally measured screech tone frequency and amplitude with remarkable accuracy (Jeun *et al.* 2022), the role of high-quality experimental measurements is becoming increasingly unclear. If experimental techniques are to provide more than simple validation for numerical codes, then they will need to be able to provide high-resolution measurements of three-dimensional structures in complex flows, flows that are challenging to simulate. The tomographic digital holographic interferometry (TDHI) technique of Léon *et al.* (2022) shown in figure 1 has the potential to do exactly that.

## 2. Overview

When jets are sufficiently far from their design condition, a large Mach disk forms in the core of the jet, producing an additional internal annular shear layer arising at the jet triple point. A screeching highly underexpanded jet then represents an extremely complex three-dimensional field: a helical Kelvin–Helmholtz vortex, a helical upstream-propagating guided-jet mode, two separate annular shear layers and a system of shocks and expansions. Léon *et al.* (2022) combined an experimental set-up of significant complexity with elegant mathematical techniques to educe not only the time-averaged flow structures of such a jet, but also the three-dimensional structure of the leading azimuthal Fourier modes of the flow. The authors implemented a TDHI technique based on an arrangement of six Mach–Zehnder interferometers. Although this is not the first application of digital holographic interferometry in underexpanded jets (Buchmann, Atkinson & Soria 2012), nor the first tomographic measurement of the density field (Nicolas *et al.* 2017), there are to the best of the author's knowledge no three-dimensional density measurements of comparable quality in the extant literature.

Though there is a common thread between the various techniques based on variations in refractive index, methods such as the classical schlieren and shadowgraphy

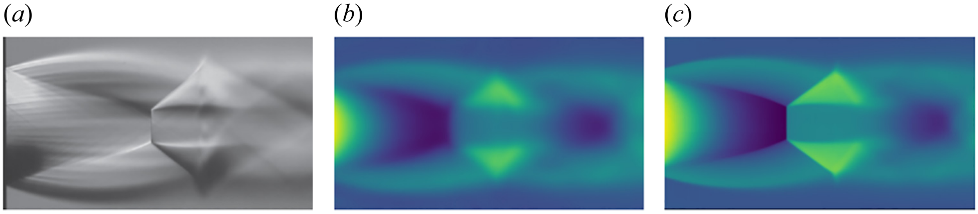

Figure 2. Comparison of mean fields extracted by: (*a*) Z-type schlieren (Edgington-Mitchell, Honnery & Soria 2014), (*b*) tomographic BOS (Nicolas *et al.* 2017) and (*c*) TDHI (Léon *et al.* 2022).

(Settles 2001) encode information about the refractive index variation in an intuitive manner; the bending of light rays by changes in refractive index is an elementary topic in high-school physics, and is relatable for anyone who has seen the air shimmering above the road on a hot day. Holographic interferometry is rather less intuitive, using the interference between a reference beam and the light passing through the jet to indirectly educe the variations of refractive index, variations that have been encoded in changes of phase of the wavefront. Though more complicated than other techniques in both experimental configuration and post-processing, digital holographic interferometry permits high-resolution quantitative measurements of the density field. In the case of axisymmetric flows, a single path-integrated measurement is sufficient to resolve the axisymmetric density field via an Abel inversion; such an approach has been used to measure the mean flow of various jets. Supersonic jets are inevitably turbulent, meaning that instantaneous snapshots of the flow can never be axisymmetric. Resolving the instantaneous fluctuations requires multiple cameras and a tomographic reconstruction. Tomographic approaches to fluid measurement have become widespread in recent years, both in particle-image velocimetry (PIV) and background-oriented schlieren (BOS) (Nicolas *et al.* 2017; Amjad *et al.* 2020). The present approach offers order-of-magnitude improvements in spatial resolution compared with either of these techniques, permitting accurate measurement of the sharp gradients associated with shocks and other structures in the jet.

As a first step, the authors used their technique to extract the mean density field of the flow. Though such a field is available from single-perspective measurements, the gradient associated with the shock is remarkably sharp when compared with data acquired using BOS or PIV; a comparison between three techniques is presented in figure 2. The present result is comparable to the Rayleigh scattering measurements of Panda & Seasholtz (1999), the previous gold standard for mean-density measurement in supersonic jets.

Where the present technique goes far beyond the capabilities of Rayleigh scattering is in permitting a Fourier decomposition in the azimuthal direction. It is now understood that the structures of relevance to noise generation in jets are low rank in azimuth (Jordan & Colonius 2013); azimuthal decomposition of both numerical and experimental data has been integral to much of our recent progress (Towne *et al.* 2017; Bogey 2021). In this work, the authors demonstrated that the azimuthal Fourier decomposition can be performed on the measurements of phase, prior to the tomographic reconstruction step; leveraging the symmetry-preserving properties of the Radon transform facilitates an elegant and computationally efficient extraction of the azimuthal modes.

Though the ‘C’ mode of jet screech has been described as ‘helical’ since the early days of jet screech, in the hydrodynamic field this was always inferred, rather than measured directly. In my own work on the C mode of jet screech (Edgington-Mitchell *et al.* 2014) using PIV, I claimed that the screech was helical, but could not demonstrate this with

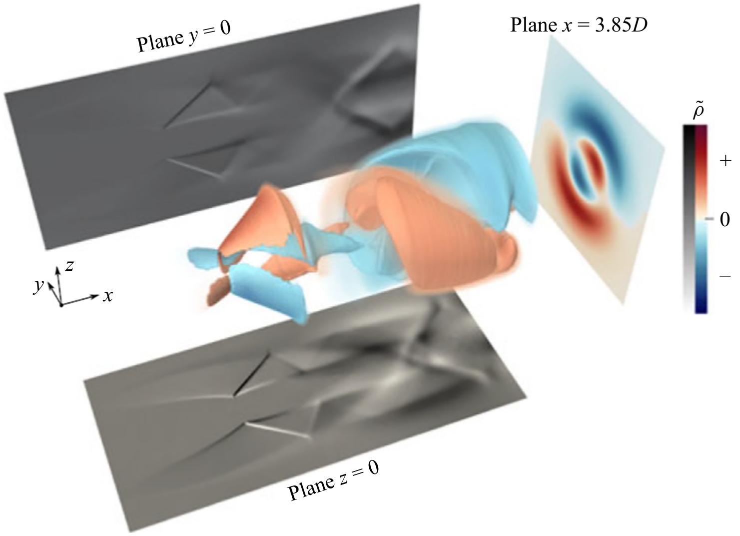

Figure 3. Three-dimensional density field associated with the $m = 1$ azimuthal mode (Léon *et al.* 2022).

any rigour. In the time since, numerical simulations have revealed a clear helical structure (Li *et al.* 2019), but until the present work, there has been no proof that the wavepacket structure of the jet was helical. The dominance of the $m = \pm 1$ mode in the results of Léon *et al.* (2022) provides at last this rigorous proof. Through the application of proper orthogonal decomposition, the authors then demonstrated that the helicity changes sign frequently during the continuous operation of the jet. This is the first time that such intermittency in rotational direction has been demonstrated for a screeching jet; prior work had indicated that although the jet might have no preferred helicity, once in operation it tended to lock to a particular direction. Further, the authors demonstrate that while the jet is equally likely to adopt either direction of rotation, one direction exhibits slightly stronger density fluctuations. This indicates that a very subtle asymmetry in the nozzle might serve to amplify the growth of structures in one direction, yet this difference is insufficient to provide a preferred direction of rotation.

The apotheosis of the paper comes in the remarkable depiction of the three-dimensional density field reproduced in figure 3, which brings to mind the iconic visualisations of the $m = 1$ mode in a swirling jet produced in Oberleithner *et al.* (2011). Here, as in that earlier paper, decompositions in both energy and azimuth have been used to construct a reduced-order representation of the flow field. Critically, however, although the representation here is low rank, it is also based on a measurement of the entire density field, with no extrapolation.

## 3. Future

To look to the future of this work, we return to the question posed earlier: what role will experiments have in a world of high-fidelity GPU-based large-eddy simulations? Certainly, validation will be required for some time to come, but those of us who have spent our lives tinkering in the laboratory aspire to be more than an accessory to numerical simulations. Experiments can still offer at least two things that (at least thus far) remain beyond the reach of numerical simulation. The first is the ability to rapidly interrogate larger parameter spaces; the development of several recent models for resonance in jets was facilitated through relatively simple measurements across wide ranges of operating conditions (Jordan *et al.* 2018). The second is the ability to measure complex three-dimensional geometries with characteristics that are difficult to reproduce numerically. The TDHI technique presented in this work has the potential to satisfy both requirements at once; acquiring three-dimensional density information across a broad parameter space in a relatively short period of time. Of course, this is not without its challenges. The authors have elegantly leveraged the azimuthal symmetry of the problem to permit efficient computation of the three-dimensional density field; interpretation of 'azimuthal' modes in non-axisymmetric geometries is not straightforward. As the authors note with some understatement when describing TDHI 'this comes at a price of a more complex set-up…'. Though setting up the optics for classical schlieren is something of an art, there is minimal need for postprocessing. By comparison, the BOS technique offers simplicity in set-up at the expense of more involved postprocessing. TDHI in a sense combines the 'worst' of both worlds; one must invest a great deal of effort in the optical set-up, and also have an in-depth grasp of the underlying mathematics. Of course, one could have said the same about tomographic PIV when it was first developed, yet tomographic PIV systems can now be bought off the shelf. While for now there may be few research groups with the necessary skillset to reproduce the approach of Léon *et al.* (2022), the remarkable quality of the results might be enough to see the technique take its place in the standard set of diagnostic tools for high-speed flows.

**Declaration of interests.** The authors report no conflict of interest.

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