Large-Scale PIV for High-Subsonic Hot Coaxial Jet Exhaust Measurements

B. Timmerman¹,²*, P.J. Bryanston-Cross², B. Falconer²

1: WMG, University of Warwick, Coventry, UK
2: OEL, School of Engineering, University of Warwick, Coventry, UK
* correspondent author: B.H.Timmermanl@warwick.ac.uk

Abstract A versatile particle image velocimetry (PIV) system is presented designed for study of high-speed large-scale complete jet exhaust flows ranging from the nozzle exit down to 20 nozzle diameters (D). The arrangement enables synchronised recording of both 3-component (3C) and 2-component (2C) PIV data allowing time-space correlations to be made, allowing for study of spatio-temporal developments in the jet, associated with jet-noise production. Results are presented obtained at QinetiQs Noise Test Facility from jet flows at engine representative model scales, both acoustic and aerodynamic, at representative velocities and temperatures.

1. Introduction

Current bypass aircraft engines generate hot coaxial jet flows, producing complex flow fields, with mixing occurring between the core and bypass flows as well as between the bypass and flightstream. Noise production in jets has been associated with instabilities or large-scale coherent structures in fully turbulent flows. These structures have long been deemed important sources of jet noise, both for supersonic (Bishop, 1971; Tam, 1971) and subsonic (Crow, 1972) regimes. The mechanisms by which instabilities radiate sound are still under investigation, especially in the subsonic regime, where vortex pairing is of particular interest. Almost all commercial aircraft currently in service operate in the subsonic or moderate supersonic regime.

Subsonic jet noise has been studied extensively (Mollo-Christensen, 1964; Bogey et al, 2009). Ongoing effort is devoted to identifying and characterising vortical structures and their relevance for noise generation. The noise producing regions of jets have been found to be dominated by large-scale coherent structures. The wavelengths, propagation speeds and radial distributions of these structures are reasonably described by local instability modes supported by the background mean flow. In a recent review Suzuki (2010) discussed the noise generation mechanisms of subsonically convecting jets. Despite extensive research providing an abundant collection of data about the characteristics of subsonic jet noise and the dynamics of large-scale structures, the understanding of the relation between them remains mainly at the level of intuitive phenomenological descriptions.

The present study investigates hot high-subsonic coaxial jets and structures associated with noise production. The paper presents results obtained using PIV at QinetiQs Noise Test Facility (NTF, Farnborough, UK) from jet flows at aircraft engine representative model scales, both acoustic and aerodynamic, at representative velocities and temperatures.

2. Measurement system

The PIV measurement systems presented here were developed to cope with hot high-subsonic coaxial jets and e.g. arbitrary nozzle/wing geometries that are of direct industrial interest to support development and validation of computational tools for predicting jet noise. To investigate the effect of different configurations the system had to withstand realistic flight conditions at up to 100m/s
flightstream The main purpose of the PIV measurements was to provide an accurate database of first- and second-order statistics of the full jet, requiring both 2C and 3C measurements to be made from nozzle exit up to 20 diameters downstream at a resolution of 5mm or better from a standoff distance of at least 2m (needed in order to stay clear of the flightstream). To accommodate the different requirements and based on previous experience (Timmerman et al. (2009), a highly versatile PIV systems were designed, which furthermore enabled the acquisition of multi-point space-time 2C-3C correlation data (e.g. Fig. 1). The system is demonstrated on a range of medium scale model engine flows generated at QinetiQ's Noise Test Facility (NTF) Farnborough, UK. This test facility is one of the world's largest anechoic chambers: 27 metres long, 26 wide and 14 metres high. This enables measurements to be taken at a representative engine model scale, both acoustic and aerodynamic. The flows that are generated are typically high-speed, high-temperature and highly turbulent.

![Schematic of 2C-3C PIV system designed for large-scale flow studies. Green: laser sheets. Blue: PIV cameras. Top: 3C measurement system, with capability for switching between upstream or downstream view. Bottom 2C system.](image1)

![Velocity distribution in engine exhaust flow measured through 2C-PIV from 0-18 D (nozzle diameters)](image2)

Working in a hostile, large scale, industrial, high-speed-flow environment imposes specific challenges to the use of these techniques that are not generally encountered in small-scale laboratory experiments. In general, as operator access to the test chamber is typically restricted or
impossible during runs, measurement systems need to be fully remotely operated. In addition, these systems need to cope with often-harsh environments involving e.g. vibration, moisture and large temperature gradients, with potentially detrimental influence on cameras and other sensitive equipment. Also, the time needed to acquire data can be prohibitive given the expensive running cost of many large scale facilities. Furthermore, such measurements at realistic scales provide an extra challenge on the image collection optics, as high-speed flows require sub-micron sized seeding particles, while in order to avoid interference with the flow all instrumentation must be placed at a sufficient distance. This is particularly true when investigating flow behaviour as related to noise production. Typically this scale implies that it is not possible to capture instantaneous images of the complete field of interest at sufficient resolution. Thus, full field statistics need to be assembled by collecting data from different areas sequentially. Figure 2 shows an example of such a compiled exhaust mapping for the mean absolute velocity, based on measurements of areas of approximately 2Dx2D (with D being the diameter of the outer nozzle, typically ~200mm).

3. PIV measurements

The main design parameter that can be used to control jet noise is the nozzle geometry. Therefore, studies are conducted into reduction of jet mixing noise through the use of castellated or serrated nozzles attached at the rear of the engine. Such exhaust nozzles influence the mixing of the hot jet exhaust and the bypass stream with the ambient air, thereby reducing jet noise. To investigate the effects, different geometries have been investigated. Figure 3 shows an example image showing the core, bypass and flightstream seeding near a baseline nozzle exit as well as an example of a section of an instantaneous 3C vector field far downstream showing the turbulent mixing.

![Figure 3: 3C PIV data examples. Left: raw data near nozzle (0.1D) showing core bypass and flightstream seeding. Right: Small section of downstream (18D) velocity map showing turbulence in fully mixed region of engine exhaust flow. Blue: low velocity, white: 280 m/s)](image)

3.1 Time-Space Correlations

Time-space correlations were obtained for the 2C axial PIV maps taken a time τ after the 3C cross-plane maps from a location Δx downstream from the 3C maps taken at position x₀. Different correlation approaches were used to analyse structural development in the flows.

Considering only the turbulent axial component, \( u' \), through:
\[
R(u)_{x-x_0,z-z_0,\tau} = \frac{u_{x_0,z_0,\tau} \cdot u_{x,z,\tau+\tau}}{\sqrt{u_{x_0,z_0,\tau}^2 \cdot u_{x,z,\tau+\tau}^2}}
\]

results in correlation maps of the type shown in Figure 3. Typically, the maps show very well defined peaks when \(z_0\) is in the inner shear layer. Furthermore, the convection velocity was found to be independent of time delay \(\tau\).

![Figure 4: Example of 3C-2C correlation map based on PIV measurements of co-axial jet flow with 3C-measurement plane at 1D. A clear peak is found in the inner shear layer.](image)

3.2 Structure analysis

To analyse the effect of different nozzle configurations, the structure distribution was investigated. For this, the instantaneous vector maps were decomposed using snapshot POD. Partial reconstructions of the vector maps were made retaining 40% of the fluctuating energy to remove fine scale turbulence. These partial reconstructions were then used to identify structures and their orientation based on an ellipse estimation that is unaffected by fluctuations in velocity direction. The resulting structure maps reveal trends in position and number of structures through the flow fields (Figure 5). As expected, structures were found to be concentrated along the mixing layers, typically tilting towards the high-velocity side. Structure size was found to increase non-linearly in the core region, while an almost linear growth was found outside the core region.

![Figure 5: Structure location and orientation (θ) as identified based on modified ellipse estimation of POD reconstructed velocity maps. Note the opposite orientation of structures on either side of the central axis as well the structures being predominantly confined to the inner and outer mixing layers (Graves, 2010).](image)
4. Conclusions

Particle image velocimetry systems are presented that enable measurements of high-subsonic, hot, large-scale coaxial jets at realistic speeds and temperatures. They encompass synchronised 2C-3C measurements, allowing space-time correlations to be made, associated with jet noise production. Furthermore, the development of vortical structures is investigated for different flow geometries.

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References