Volumetric Vector Velocity Measurements in a Hot Supersonic Jet

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A new variant of Doppler global velocimetry, cross correlation DGV (CC-DGV) is used to generate volumetric mean velocity maps in supersonic jets via spatial scanning. While the technique is not unique in its ability to achieve such results, the method presented is powerful for efficient, high-resolution mean flow mapping. In the full article, a volumetric reconstruction of a highly over-expanded cold jet is presented, allowing for three-dimensional visualization of the breakdown of the potential core region of this flow. Additionally, stream-wise velocity data on the development of the shear layer in an over-expanded hot supersonic jet are presented which provide detailed information on the shear layer growth rate, a quantity which has been shown to be affected by compressibility and indicative of compressibility effects related to turbulent mixing reduction.

The Virginia Tech hot jet facility was recently built in support of various research thrusts related to propulsion, aeroacoustics, and fundamental aerodynamics. The facility features interchangeable nozzles and capable of a wide range of total temperature and pressure ratios. Mean velocity maps are important for this type of facility to complement point measurements and define flow-field development. The value of the mean velocity maps is not trivial and obtaining them has time been consuming, done either using point probes (optical or pressure) or with PIV. In the Virginia Tech facility, high frequency LDV and point-DGV are currently used for this mapping, supplemented with qualitative Schlieren images for global flow-field context. CC-DGV offers a quantitative way to locate features such as shocks and shear layers while also providing a baseline velocity for validation of unsteady point measurements. Further, Papamoschou & Roshko (1988) and Freund et al. (2000) have shown that the shear layer spreading rates obtained from mean velocity measurements are well-correlated to both mean and radial turbulence Mach numbers, providing a means for exploratory examination of eddy convection velocities and radial turbulence levels, informing decisions for conditions to obtain detailed measurements.

Cross-correlation DGV was developed by Cadel et al. (2014) for spatially resolved mean velocity measurements. The paradigm shift in CC-DGV comes in acquisition and processing of data with time as the independent parameter, in contrast to more conventional intensity-based DGV measurements (although similar to the FM-DGV technique). Intensity values are still directly measured; however, it is the time-based differences between corresponding signals that are used to determine Doppler frequency shift (Figure 1).

Monte Carlo simulations were performed simulating the Doppler frequency shift as measured by individual sensors. Absorption cell temperature mismatches are studied for variations of ± 20°C, and insensitivities comparable to existing methods are found without temperature control provided a transmission ratio threshold is met. The technique is further shown to be versatile to measure velocities from low subsonic to supersonic regimes independently within the same field of view. The cross-correlation function is insensitive to absolute intensity mismatches between the Doppler shifted and reference signals. Bias errors in the correlation function peak-finding algorithm have also been investigated. An uncertainty analysis was performed for the specific experimental configuration used in this work for free-stream flows of 10 ms, 100 ms, and 500 ms flows.

For cold conditions (M=1.65, NPR = 2.7, TTR = 1.0), a volumetric reconstruction of the jet is presented centered around a location 4 diameters downstream of the exit plane, encompassing the entire radial cross-section of the jet (Figure 2). Planar results for a cross-section parallel to the flow direction at the nominal centerline are presented for hot conditions (M=1.65, NPR = 2.7, TTR = 2.0). Multiple imaging planes are meshed together to achieve a global context encompassing diameters and providing for measurement of near-nozzle shear layer development.

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