EVOLUTION OF COHERENT STRUCTURES IN UNDER-EXPANDED SUPERSONIC IMPINGING JETS

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Abstract This study looks at the spatio-temporal dynamics of the coherent structures found in under-expanded supersonic impinging jets from a circular nozzle at a pressure ratio of 3.4 and standoff distances of $\{2d, 5d\}$. In these jets the development of coherent structures within the shear layer and their interaction with a standoff-shock are the principle components of a fundamental non-linear acoustic feedback mechanism. Temporally resolved and phase averaged data for each case was generated from a three dimensional hybrid large-eddy simulation on a non-uniform structured cylindrical grid with computational domains consisting of approximately 30 million nodes. From these datasets we investigate the development of the energy, topology and turbulence interactions of the coherent structures as a function of their distance travelled along the shear-layer.

INTRODUCTION

Under-expanded supersonic impinging (USI) jets characteristically produce large-scale structures at discrete frequencies due to the development of an acoustic feedback mechanism. In this feedback loop acoustic waves generate an instability at the nozzle lip which grows within the shear layer as it travels downstream. These structures interact with the stand-off shock which produces a disturbance in the wall jet. An acoustic wave is then generated in the wall jet which travels upstream and restarts the cycle. The most significant parameter for USI jets is the standoff distance (z) between the nozzle outlet and the impingement surface. Changes in z produces staging behaviour between different instability modes and their associated frequencies.

A majority of prior research into USI jets has centred around the analysis of the mean flow field, prediction of the acoustic tone frequencies and coherent structure topology through dynamic mode decomposition [8, 2, 4]. However, it is important to understand the dynamics and interactions involved in the development of the large-scale coherent structures in these jets due to their importance in the acoustic feedback mechanism. This study looks into the evolution of the coherent structures along the shear layer as well as their interaction with the mean flow field and the broadband jet turbulence. In order to undertake this analysis, time resolved data has been generated at standoff distances of 2 and 5 nozzle diameters (d) while at a nozzle pressure ratio of 3.4, exit Mach number of $M_e = 1$ and a jet Reynolds number of $\text{Re}_D = c_e d\rho/\mu = 50,000$

NUMERICAL METHODOLOGY

An in house three dimensional high fidelity compressible LES solver for non-uniform structured meshes was used to generate the dataset utilized in this study. For spatial differentiation the hybrid solver employs a sixth order central finite difference scheme for smooth regions and a fifth order weighted essentially non-oscillatory scheme with local Lax-Friedrichs flux splitting in discontinuous regions. Temporal integration is performed using a fourth order five step Runge-Kutta scheme. The sub-grid scale terms were computed using Germano's dynamic model with the adjustments made by Lilly [5]. The domain consists of approximately 30 million nodes with the spatial extent of $15d$ the radial direction. Locally one-dimensional inviscid compressible boundary conditions defined in [7] are outflow regions. Sponge regions are employed near the outflow boundary were the flow field is forced to a self similar incompressible wall jet solution that has been determined *a priori*.

RESULTS

A plot of the temporal mean velocity and velocity fluctuation magnitudes for both standoff distances may be found in Figure 1. The black markers in Figure 1 denote the sampling positions for the sound pressure levels plotted in Figure 2(a-b). Five dominant modes, denoted by the coloured vertical lines, are present in the $z/d = 2$ case while two modes are present in the $z/d = 5$ case. A temporal Fourier decomposition was performed at predetermined sampling positions as a function of the distance along the shear layer (s). Sample positions were placed at the point of maximum fluctuating velocity in the shear layer as is seen in Figure 1 in which every fifth sample position has been plotted as a white marker. The variance of the Fourier modes associated with the dominant modes in the jet are plotted in Figure 2(c-d) in which the vertically dashed lines denote the shock reflection points. Initially, each of the dominant modes in both cases exhibit two linear growth regions with the transition occurring between $0.3 \leq s/d \leq 0.4$. The growth of all modes ceases around the first shock reflection point where strong non-linear effects are evident. Finally, despite large differences in the initial instability magnitude the final magnitudes are similar.

In order to understand the effect of the mean flow field on the coherent structure a global instability analysis will be performed in which the frequency has been set to those of the instabilities present in each jet. Interactions with the turbulence present in the jet will be investigated using the resolvent model that has been applied by [6] to wall turbulence.

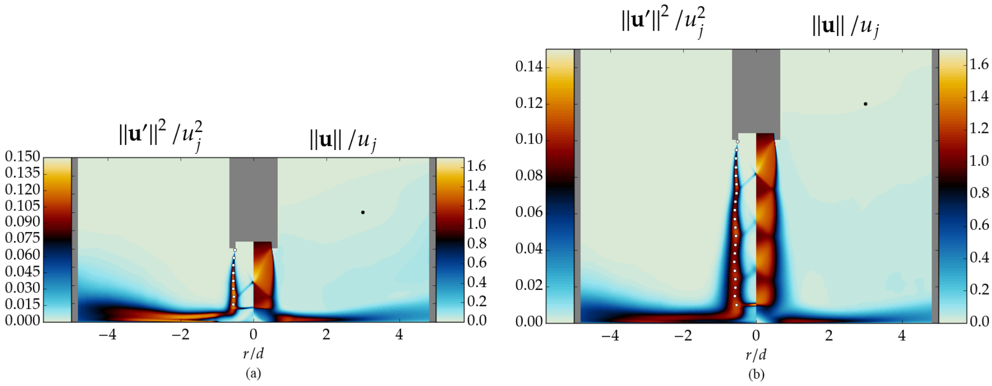

Figure 1. 2D slices of the temporal means of the velocity magnitude (right halves) and square of the velocity fluctuations (left halves). The black dot represents the sound pressure level sampling position and the white dots represent every 5th sample position along the shear layer used in the spectral analysis. (a) $z/d = 2$ (b) $z/d = 5$.

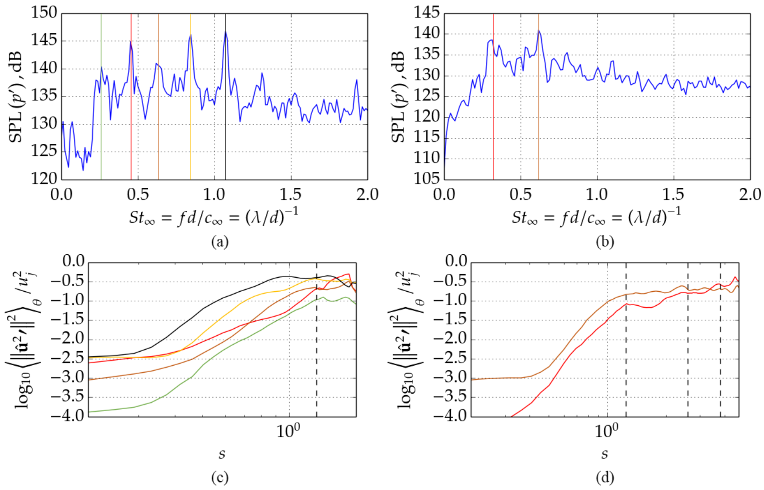

Figure 2. (a-b) Sound pressure levels. The coloured vertical lines denote the dominant modes of the jet. (c-d) Variance of the Fourier modes associated with the dominant modes of the jet. Colours are associated with the modes in (a-b). Vertically dashed lines denote the shock reflection points. (a & c) $z/d = 2$ (b & d) $z/d = 5$.

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