A Study of the Noise Source Mechanisms in an Excited Mach 0.9 Jet - Complementary Experimental and Computational Analysis

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The abstract goes here...

I. Introduction

II. Experimental Setup

Experimentation was conducted in the free jet facility (a schematic of which can be found in Fig. 1) at the GDTL within the Ohio State University's Aerospace Research Center.The dimensions of the chamber are 5.14 m wide by 4.48 m long and 2.53 m high (wedge-tip to wedge-tip). The design of the chamber produces an anechoic cutoff frequency of 160 Hz, below the frequencies of interest for this study. Additional details of the facility design and validation can be found in Hahn.[1] Compressed, dried, and filtered air is supplied by two cylindrical storage tanks with a total capacity of 43 m^3 and maximum pressure of 16 MPa; the tanks are charged by three, five-stage reciprocating compressors. The air enters the facility horizontally, passes through a stagnation chamber and turbulence screens, and exhausts through a converging nozzle. Opposite the nozzle, a collector accumulates the jet and entrained air and exhausts to the outdoors.

A converging, axisymmetric nozzle with exit diameter of 25.4 mm was used in the current study. The internal contour of the nozzle was designed using a fifth order polynomial. The nozzle utilized a thick-lipped design in order to simplify the mounts for the LAFPA extension, which housed the eight actuators used in this study.For the experiments reported in this paper, the jet was operated at a Mach number, M_j, of 0.90, and with a total temperature ratio of unity.The Reynolds number based on the jet exit diameter was 6.2×10^5; previous investigations using hot-wire anemometry have indicated that the initial shear layer is turbulent for this operating condition with momentum thickness 0.09 mm and boundary layer thickness 1 mm.[2]

III. Computational Model

The simulations employ the same approach as previously used to simulate a Mach 1.3 jet without and with control.[3,4] The full compressible Navier-Stokes equations are solved in curvilinear coordinates (ξ, η, ζ) using the strong conservative form.[5,6] The transformed non-dimensional equations in vector notation are given as:

$$\frac{\partial}{\partial \tau}\left(\frac{\vec{U}}{J}\right) + \frac{\partial \hat{F}}{\partial \xi} + \frac{\partial \hat{G}}{\partial \eta} + \frac{\partial \hat{H}}{\partial \zeta} = \frac{1}{Re}\left[\frac{\partial \hat{F}_v}{\partial \xi} + \frac{\partial \hat{G}_v}{\partial \eta} + \frac{\partial \hat{H}_v}{\partial \zeta}\right] \tag{1}$$

where $\vec{U} = \{\rho, \rho u, \rho v, \rho w, \rho E\}$ denotes the solution vector and $J = \partial\left(\xi, \eta, \zeta, \tau\right)/\partial\left(x, y, z, t\right)$ is the transformation Jacobian. Details of the various terms in Eqn. 1 may be found in Speth and Gaitonde.[7] For the inviscid terms, a third-order upwind biased approach is adopted, together with the Roe scheme[8] for flux

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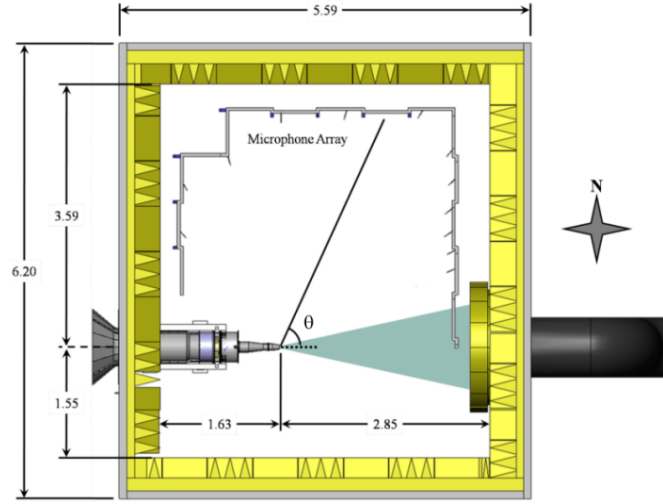American Institute of Aeronautics and Astronautics

Figure 1: Plan view of GDTL free jet facility; dimensions in meters.

evaluation. The limiter required to enforce monotonicity is a crucial component of the method. The van Leer harmonic limiter[9] has proven to be very successful at reproducing the main features of the unsteadiness in the jet. The viscous terms are discretized with second-order centered differences and time integration is performed by a second-order diagonalized[10] approximately factored method.[11] A sub-iteration strategy is used to minimize errors due to factorization, linearization and explicit boundary condition implementation.
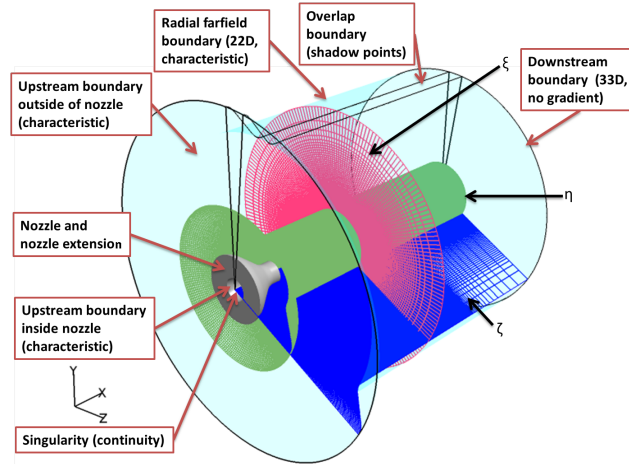

Figure 2: Computational domain

A 65 million point mesh (Fig. 2) is used to simulate the Mach 0.9 jet measured in the experiment (Fig. ??a). The grid has dimensions of 685 points on the ξ (streamwise) direction, 455 points in the η (radial) direction, and 209 points in the ζ (azimuthal) direction. In the radial direction, the mesh is refined in the nozzle region and gradually stretched in the far field. At the exit of the nozzle, the grid maintains a constant axial spacing until after the potential core length; then stretches in the streamwise direction as well. To preserve continuity, the grid has a five point overlap in the ζ direction. Characteristic boundary conditions[12] are applied to the upstream (outside the nozzle) and radial boundaries. Non-reflecting conditions are applied to the downstream and far-field boundaries. Stagnation conditions are specified at the first ξ plane of the nozzle ($\rho_{inlet} = 2.04 kg/m^3$, $U_{inlet} = 22 m/s$, $P_{inlet} = 171,427 Pa$) to achieve perfectly expanded nozzle

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exit conditions corresponding to $\rho_{jet} = 1.404kg/m^3$, $U_{jet} = 285.99m/s$, $T_{jet} = 251.31K$ which match the experiments. Based on the nozzle diameter therefore, the Reynolds number is $Re = 635,308$. The nozzle geometry resembles that of the experiments including the nozzle ring on which the actuators are mounted. The velocity profile at the entrance to the nozzle is that of a uniform flow (zero at the wall and U_{inlet} everywhere else). Perturbations were not introduced into the inflow due to the unknown perturbations in the experiment. Therefore, the simulations have a laminar boundary layer at the nozzle exit while the experiments have a very thin turbulent boundary layer (the momentum thickness has been estimated to be $0.09mm$). Previous studies have shown that despite this difference, the main features of the experimental observations are successfully reproduced by the computations.[3,4] Other studies have shown that a smaller 32 million point simulation is adequate to reproduce the features of the experiment.[13]
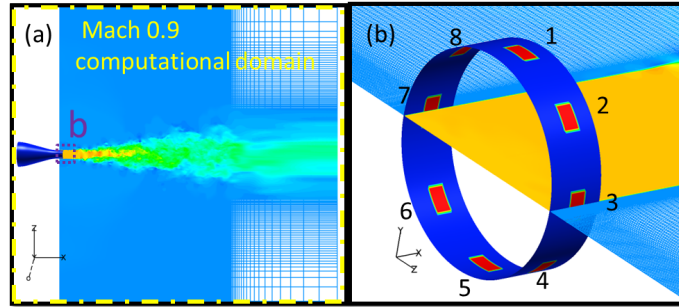

Figure 3: The computational domain including the nozzle (a), and the numerical actuator model (b)

The LAFPAs are modeled after the experiments using a surface heating technique to excite jet shear layer instabilities and azimuthal modes within the jet. Eight actuators are placed around the periphery of the jet on the nozzle collar at the locations and dimensions of the experiments as explained above in Section **??**. As shown in Fig. 3b, each actuator consists of a heated region of the nozzle wall which extends the azimuthal length corresponding to the separation distance between electrodes ($3mm$) and has an axial extent equal to the length of the groove ($1mm$). The temperature of the nozzle wall was assumed to be $1.12T_\infty$. When the actuator is on the temperature of the actuator region increases to $5T_\infty$. Little difference was seen in the previous work (Speth and Gaitonde[14]) for the temperature range measured in experiments (Utkin *et al.*[15]) for a Mach number of 1.3. The semi-empirical model is necessary to avoid first-principles simulation of the poorly understood plasma heating process, as well as to restrict the required computational resources to feasible levels (see Ref.[16]).

Unlike acoustic drivers, the LAFPAs are on-off devices and thus can be represented by rectangular pulses with a duty cycle, which allows for a wide range of operation choices. Duty cycle is the percentage of actuator on time in an excitation cycle. Therefore, a duty cycle of 100% results in the actuator being on all the time. The experimental duty cycle varies with frequency, since the arc strike lasts a fixed time. Since the actuator model is empirical, the computational duty cycle was chosen to obtain similar control authority as in the experiment. This necessitates a higher duty cycle (10%) than the one used in the experiments (2.0% for $St_{DF} = 0.25$). As noted earlier, despite the simplicity of the model, its success has been documented in Gaitonde and Samimy,[3] where, in addition to coherent structures, mean and fluctuating quantities have been compared. Furthermore, the mean flow structure with control was shown to match the theoretical predictions of Cohen and Wygnanski.[17]

Like the experiments, the axisymmetric ($m = 0$) mode was employed to study a range of Strouhal numbers. The Strouhal numbers studied in the simulations include: 0.05, 0.15, and 0.25. Data was acquired every timestep at the point probes depicted in Fig. **??**b as well as on several ξ, η, and ζ computational planes. Phase-averaged data were also computed for each of the simulations.

IV. Results

Acknowledgments

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