AIAA Journal
Vol. 47, No. 11, November 2009

Assessment of Computational Fluid Dynamics for Supersonic Shock Containing Jets

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DOI: 10.2514/1.44336

This paper describes a combined experimental and computational investigation of supersonic jets operating off design. Axisymmetric steady-state computational fluid dynamics simulations were performed with a Reynolds-averaged Navier–Stokes solver using a two-equation turbulence model. These results were compared directly with experimental results for two differen t axisymmetric nozzles operating at over- and underexpanded conditions. Pitot and static pressure probes were used to measure the Mach number and local static pressure at various downstream locations. A comparison of both experimental and numerically predicted schlieren visualizations were performed for a qualitative assessment of the accuracy of the flowfield predictions. Quantitative comparisons of pitot and static pressures were made between the experiments and simulations. This provides an assessment of the quality of the numerical simulations as well as an indication of the errors associated with any interference between the pressure probes and the flow in the experiments.

Nomenclature

a_∞ = ambient speed of sound
a_j = speed of sound at nozzle exit
D = diameter of nozzle exit
D_p = diameter of static pressure probe
k = turbulent kinetic energy
M_d = design Mach number of nozzle
M_j = fully expanded jet Mach number
M_1 = local Mach number
P_p = local pitot pressure
P_{to} = total pressure in the plenum
P_{t1} = local total pressure
P_{t2} = local total pressure behind a normal shock
P_1 = local static pressure
P_∞ = atmospheric pressure
T_o = jet stagnation temperature
T_∞ = atmospheric temperature
U_j = mean exhaust velocity
x = downstream direction, coordinate
x_h = location of static pressure ports
y = cross-stream direction, coordinate
y^+ = coordinate in viscous wall layer
z = observer direction, coordinate
β = nozzle off-design parameter
γ = ratio of specific heats
ρ = local density

Introduction

THIS paper describes a combination of experimental and computational study of supersonic jets operating off design. The motivations for the work are twofold. First, the results of the numerical simulations form the basis for a prediction model of Broadband shock-associated noise (BBSAN) presently under development by the authors. This model requires a knowledge of the time-averaged velocity field, the pressure perturbations associated with the shock cell structure, as well as information about the turbulence length and time scales, which can be obtained if a two-equation turbulence model is used. Second, it is known that the presence of pitot and static pressure probes in the turbulent flow may interfere with the natural development of the jet. Once confidence has been established in the numerical simulations, they can be used to indicate locations in which experimental measurement are less reliable and the reasons for this decrease in accuracy.

A series of pitot and static pressure probe measurements have been conducted and compared with CFD simulations at various downstream and cross-stream locations. Quantitative comparisons are made with profiles and contour plots of the local Mach number M_1 and local static pressure P_1. Schlieren images of the jets are compared with density gradients calculated from the numerical simulation database. Finally, the calculated database is used to predict profiles and contours of a local stagnation pressure behind a local normal shock wave. This quantity P_{t2} can be compared directly with the experimental pitot pressure as additional evidence of the quality of the computations. The measurements are performed for two imperfectly expanded jets issuing from two different nozzles: a converging nozzle with a design Mach number M_d of 1.0 operating at a fully expanded Mach number M_j of 1.5, and a converging–diverging nozzle with $M_d = 1.5$ and $M_j = 1.3$. The nozzle pressure ratios (NPR) for these two jet conditions are $P_{to}/P_\infty = 3.67$ and 2.77, respectively. The total temperature ratio for both jets is $T_o/T_\infty = 1.00$. Both nozzles are axisymmetric, and axisymmetric CFD simulations are conducted to obtain solutions to the time-averaged equations of motion. Such steady calculations require significantly less computational time compared with time dependent calculations that have been used in the past for direct calculations of the flow and radiated noise. This provides the potential for relatively rapid predictions of BBSAN once the noise prediction models are fully implemented.

BBSAN is one of two components of shock-associated noise found in supersonic jets operating off-design. The other is screech, which is often not a concern in aircraft engines due to their geometry and high temperature ratios. There have been two moderately successful BBSAN models developed to date. Harper-Bourne and Fisher [1] proposed a theoretical model which regarded each shock/shear layer interaction as a source of acoustic radiation. In the basic model, each source is equally spaced. In their experiments, they

Presented as Paper 2988 at the 14th AIAA/CEAS Aeroacoustics Conference, Vancouver, BC, Canada, 5–7 May 2008; received 12 March 2009; revision received 24 July 2009; accepted for publication 24 July 2009.

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