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Numerical Investigation of Synthetic-Jet Flowfields

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The flowfields surrounding a synthetic-jet actuating device are investigated numerically by direct simulation. Solutions are obtained to the unsteady compressible Navier–Stokes equations for both the interior of the actuator cavity and for the external jet flowfield. The interior results are generated on an overset deforming zonal mesh system, whereas the jet flowfield is obtained by a high-order compact-difference scheme. Newton-like subiterations are employed to achieve second-order temporal accuracy. Details of the computations are summarized, and the quality of the results is assessed via grid resolution and time-step size studies. Several aspects of the actuator configuration are investigated, including cavity geometry and Reynolds number. Differences between two-dimensional and three-dimensional external unsteady flowfields are elucidated, and comparison is made with experimental data in terms of the mean and fluctuating components of the jet velocity.

Nomenclature

A = amplitude of cavity deformation
d = jet nozzle length
f = forcing frequency of cavity oscillation
g = analytic jet exit velocity spatial distribution
h = jet nozzle width, 0.5 mm
M_∞ = reference Mach number, 0.065
Re = reference Reynolds number, $\rho_\infty u_\infty h/\mu_\infty$
u, v, w = nondimensional Cartesian velocity components in x, y, z directions
u_∞ = reference velocity, 22.0 m/s
w' = fluctuating velocity component in the z direction
x, y, z = nondimensional Cartesian coordinates in transverse, spanwise, and streamwise directions
x_L = nondimensional cavity width
y_B = nondimensional jet nozzle half-span
z_B = nondimensional instantaneous cavity lower boundary position
z_D = nondimensional mean cavity depth
Δt = time-step size
$\Delta x, \Delta y, \Delta z$ = mesh spacing in x, y, z directions
Ω_y = component of vorticity in y direction
ω = nondimensional circular oscillation frequency, $2\pi f h/u_\infty$

Subscripts

cl = evaluated at jet centerline
j = evaluated at jet nozzle exit

Superscript

$\overline{}$ = time-averaged quantity

Introduction

JETS composed entirely of entrained ambient fluid may be synthesized by the formation of a time-harmonic train of vortices, which are created at the edges of a sharp orifice. Such jets operate without net mass flux across the orifice and can be produced by sound-wave transmission through the fluid, a phenomenon referred to as acoustic streaming, or by oscillation of the boundaries confining an otherwise quiescent medium. Synthetic jets may be generated for practical circumstances by a dynamic fluid actuator consisting of an enclosed cavity with a movable boundary, which is vented by a nozzle aperture. Because such devices have minimal power requirements and do not rely upon a supply of injected fluid to produce jet-like structures, they are attractive as a means of mixing enhancement in both open and closed flow systems and for convecting heat away from solid surfaces. Additional applications demonstrating active flow control include the vectoring of adjacent coflowing jets,[1] the generation of lift and drag reduction on cylinders,[2,3] the management of vortices on forebodies at high angle of attack,[4] and the delay of stall on airfoils.[5]

The development of jets with zero net mass flux have resulted from a number of investigations employing various experimental techniques. Among these are the efforts of Mednikov and Novitskii[6] who used an oscillating piston and bellows mechanism in a resonant cavity, and those of Ingard and Labate[7] applying an orifice plate to an acoustic impedance tube. Lebedeva[8] transmitted sound waves through a pipe, and Sheen et al.[9] created streaming by an oscillating ultrasonic transducer in water. More recently, James et al.[10] considered a round turbulent jet produced by a resonantly driven actuator disk.

Basic features of a synthetic-jet actuator flowfield are illustrated schematically in Fig. 1, which depicts the cross section of a three-dimensional rectangular device. The apparatus consists of a jet orifice opposed on one side by an enclosed cavity, whose lower boundary is vertically deformed in a periodic manner. Ambient fluid from above enters and exits the cavity through the jet aperture. Upward motion of the boundary produces flow, which separates at the sharp edges of the orifice and rolls into parallel vortices on either side as fluid is ejected from the cavity. These vortices then begin to propagate away from the orifice under their own self-induced velocity.[11] During downward motion of the boundary, the vortex pair has traveled sufficiently far from the orifice so as to be unaffected by the surrounding fluid that is then drawn into the cavity.

Over each cycle of operation, the net mass flux across the orifice is zero while the momentum of the vortices is nonzero. The resulting train of vortex pairs created by the actuator therefore has a time-mean streamwise velocity profile that is similar to that of a steady jet. Experimental observation[1] has indicated that, whereas the parallel vortices do not undergo pairing, they do break down and lose their individual identities at short distances from the orifice. Analysis of the frequency spectra of such jets suggests that this breakdown is caused by spanwise instabilities of the vortex cores.[1]

In addition to its utility as a control apparatus, the synthetic jet is also intriguing because of the intricate fluid physics that is exhibited in its evolution. The purpose of the work presented here is to

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