High-Fidelity and Reduced Models of Synthetic Microjets

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ABSTRACT

Microfabricated arrays of synthetic jets are being explored for applications in aerodynamic flow control, in cooling of electronic packages, and in mixing in microchemical reactors. Computational simulation of coupled unsteady fluid mechanics and electromechanical actuation of a single synthetic jet can be performed with available CFD tools. Modeling of flow physics of large arrays of synthetic jets is computationally very challenging. This paper presents two complementary computational techniques: a three-dimensional high-fidelity model for detailed simulation of a single jet, and a reduced "single-cell" model of a jet for simulation of large arrays of synthetic jets. The high-fidelity model is also used to calibrate the compact model. The paper shows examples of multi-dimensional simulations of aerodynamic flow control ("virtual flight control") and of active electronics cooling with 2D arrays of synthetic jets.

Keywords: synthetic jets; microjets; CFD simulation; reduced models; active flow control.

1 INTRODUCTION

Synthetic jets are generated at the orifice of a partially open cavity with an oscillating membrane wall opposite to the orifice opening as shown schematically in Figure 1 [1]. Microfabricated arrays of synthetic jets are being explored for applications in aerodynamic flow control, in cooling of electronics packages, and in mixing in microchemical reactors.

The synthetic jet has several unique aerodynamic characteristics, which let this small-scale device influence large scale flow fields. They have cycle average zero-mass-flux but finite momentum flux. During the suction period the fluid enters the jet orifice as a potential flow and exits the jet during the expulsion period as a highly directed jet that forms a traveling vortex ring in the external environment. The jet can penetrate and affect the surrounding environment to a distance of tens of orifice sizes (Figure 2).

When positioned at a critical point on the body, e.g., separation point, leading edge, and others, it can totally change the flow pattern around the body, e.g., it can suppress separation region, change the laminar-turbulent transition region, or induce large scale Counada flow patterns. Microfabricated arrays of synthetic jets integrated with sensors, actuators, control systems and driving electronics can be used as a powerful tool in flow control (Fig. 3) in aerodynamic applications [2].

Synthetic jet arrays can also be used in a range of other areas such as active cooling of electronic packages, mixing device in microelectromechanical systems (MEMS), device for chemical reaction control, and others. Computational and experimental evaluation of synthetic jets in electronics cooling has been recently undertaken by CFDRC and Georgia Tech., under the DARPA "HERETIC" program. Addressable array of synthetic jets impinging on a hot surface of an electronic package could be an attractive cooling scheme for high power high density electronics.

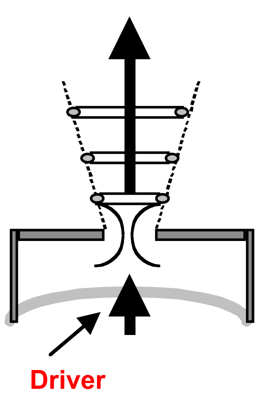

Figure 1. Schematic of synthetic jet operation.

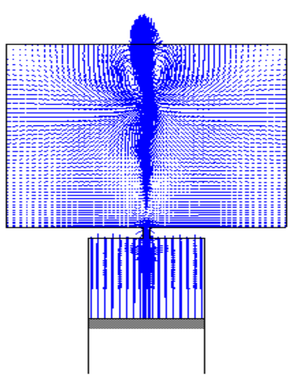

Figure 2. High-fidelity simulation of a synthetic jet using CFD-ACE+.

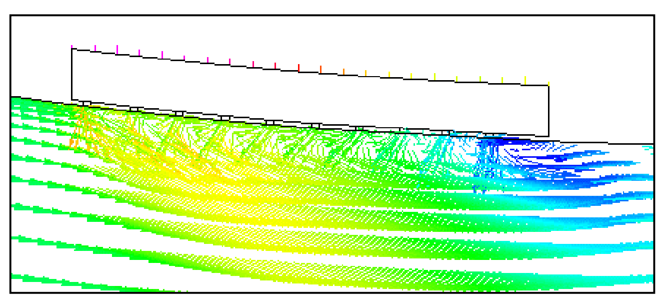

Figure 3. An array of synthetic jets in high-fidelity 3D simulations of an airfoil, with the use of reduced models in CFD-ACE+.

1.1 Design Techniques for Synthetic Jets

Design process of synthetic jets is very time consuming and heavily relies on trial-and-error experimental tests. It is generally recognized that reliable computational modeling tools can significantly shorten the design cycle and accelerate technology transition from the academic laboratories to practical commercial products. The objective of this paper is to present new modeling concepts implemented in CFD-ACE+MEMS software for synthetic jet arrays.

In recently reported computational simulations of synthetic jets either a single jet was analyzed or an arbitrarily specified jet orifice flow pattern was assumed for a row of jets [2, 3, 4]. This paper demonstrates that a reduced dimensionality model of a synthetic jet using a single control volume or a 1D model can be used to model large number of jets in an accurate and cost effective manner. The paper presents two complementary techniques: a high-fidelity CFD-based model and a reduced (compact) model, and demonstrates them on practical applications.

2 HIGH-FIDELITY MODEL

The unsteady flow dynamics inside the cavity of the synthetic jet is analyzed with the CFD-ACE+ software [5]. The code provides multi-disciplinary simulation capability by coupling: fluid flow, heat transfer, mixing and chemistry, stress/deformation, electrofluidics, electrostatics, electromagnetics, and other discipline field solvers specifically adapted for MEMS [6, 7]. The fluid flow model solves the time dependent continuity equation, the pressure-based Navier-Stokes equations, and energy balance equation. In the present formulation they are written in a strong conservation integral form on time dependent arbitrary moving/deforming geometry, and are equally applicable to incompressible and compressible flows. Numerical solution of this equation set requires discretization of the computational domain into a large number of generalized control volumes. To allow full freedom in the control volume shapes, the governing equations are expressed in the integral flux form:

$$\frac{\partial}{\partial t}\int_v \rho\, dv + \oint_\sigma \rho\left(\overline{V} - \overline{V}_g\right)\cdot\overline{n}\, d\sigma = 0$$

$$\frac{\partial}{\partial t}\int_v \rho u_i\, dv + \oint_\sigma \rho\left(\overline{V} - \overline{V}_g\right)\cdot\overline{n}\, u_i\, d\sigma = -\oint_\sigma p n_i\, d\sigma + \oint_\sigma \tau_{ij} n_j\, d\sigma + \int_v f_i\, dv$$

$$\frac{\partial}{\partial t}\int_v \rho h_t\, dv + \oint_\sigma \rho\left(\overline{V} - \overline{V}_g\right)\cdot\overline{n}\, h_t\, d\sigma = \oint_\sigma q_j n_j\, d\sigma + \int_v \frac{\partial p}{\partial t} dv + \oint_\sigma \tau_{ij} u_j n_i\, d\sigma + \int_v f_i u_i\, dv$$

$$\tau_{ij} = \left(\mu + \mu_t\right)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_j}\right) - \frac{2}{3}\left(\mu + \mu_t\right)\left(\frac{\partial u_k}{\partial x_k}\right)\delta_{ij} \qquad (1)$$

$$q_j = k\frac{\partial T}{\partial x_j}$$

where u_i is the ith Cartesian component of the velocity, V_g is the grid velocity due to grid motion, p is the static pressure, h_t is the total enthalpy, τ_{ij} is the stress tensor for both laminar and turbulent flows and f_i is the ith Cartesian component of body force. For turbulent flows, the Reynolds stress tensor is closed with a standard k-ε model. An implicit second order time-space control volume discretization method is used to solve the above equations on unstructured meshes.

The equations are solved using CFD-ACE+ software developed at CFDRC with specific application for MEMS. A unique feature of the flow solver is the application of generalized polyhedral control volumes for super resolution of jet cavities with a single control volume with large number of faces (cavity walls, membrane, orifice, …).

A moving wall and deforming grid method is used to model the interior of the cavity and a free space environment is used to model the jet evolution (Figure 2). The oscillating membrane is periodically ingesting and expelling the air from the cavity. Several oscillation cycles are performed to obtain cycle independent results. The model is validated against the experimental data obtained at Georgia Tech [1] for the jet actuated with 1 kHz oscillation frequency. Unsteady flow fields have been experimentally measured using Particle Image Velocimetry (PIV) technique.

Transient computational simulations have been performed with membrane deformation dynamics represented as a moving wall with prescribed harmonic motion. As the membrane dynamics could not be measured in the experiments, a direct comparison between computational and experimental data was not possible. Instead, several computational runs were performed to match the maximum flow rate through the orifice with a membrane displacement as a parameter. A comparison between experimental and computational vortical flow structures at two selected time instances is presented in Figure 3. Time average velocity profiles at several axial locations, measured at Georgia Tech, and calculated with CFD-ACE+. Considering the uncertainty of boundary conditions and assumed membrane dynamics, good agreement between predicted and experimental velocity profiles has been achieved [8].

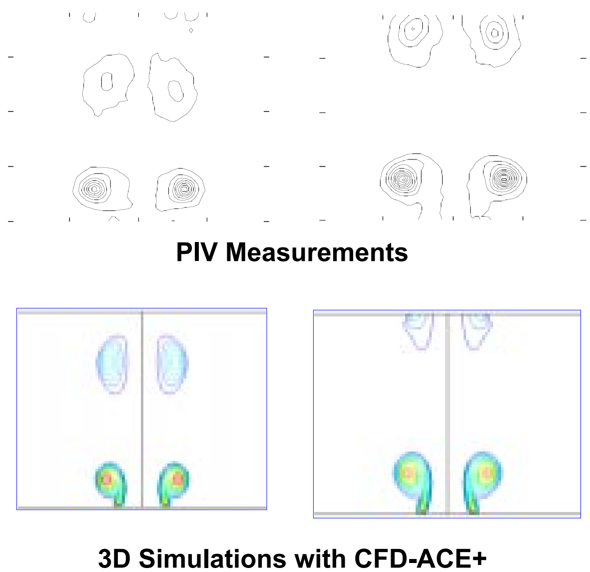

Figure 3. Synthetic jet simulation results compared to measurements: vorticity contours in time.

3 REDUCED AND COMPACT MODELS

Computational modeling of large numbers of synthetic jet cavities with high fidelity 3D models is not practical because of large computational cost. A "compact model" accounting for all essential physics expressed in terms of algebraic equations, or ordinary differential equations, is needed to model large arrays of jets. There are several approaches to formulate a compact model including analytical solutions, curve fits to experimental data, or equivalent electrical circuits. Equivalent circuit models of air dumping for inertial sensors have been recently demonstrated by the authors [9].

In this paper, we present a novel concept of mixed-dimensionality approach combined with the polyhedral grid capability to model a synthetic jet with a single control volume or a one-dimensional approximation. Both capabilities have been implemented in CFD-ACE+MEMS tool. In the proposed approach, to represent the cavity, a single control volume (CV) fully conforming to the cavity geometry is used. This single polyhedral CV, however, has a large number of cell faces, some of them are fixed wall segments, the vibrating membrane, or the orifice opening. Full set of general conservation equations (mass, momentum, energy) is solved in a single cell in time-accurate manner. The cavity volume is linked through the orifice with the external flow field in a fully implicit manner resulting in a robust simulation algorithm. If a desired accuracy of the compact model is achieved, a large number of cavities can be modeled in a very cost effective manner.

Our initial studies of compact models of synthetic jets showed that for the present configuration a two-cell model (chamber and orifice) was needed for the cavity, and an additional domain for the external environment (surrounding air) - see Figure 4. An extensive comparison of computational mesh requirements and CPU times for 3D, 1D and one-cell models was presented in [8]. CPU savings for a single cell when compared with the 3D (full cell) model are up to 100 times. One of the model requirements is good accuracy for widest possible operating range (frequency, displacement, pressure level, geometry, etc.). Computational studies showed that for small frequencies (up to 200 Hz) incompressible and compressible flow models are very similar. For higher frequencies, large discrepancies in flow rate have been observed. We recommend that a compressible version of the model should be used for entire range of frequencies.

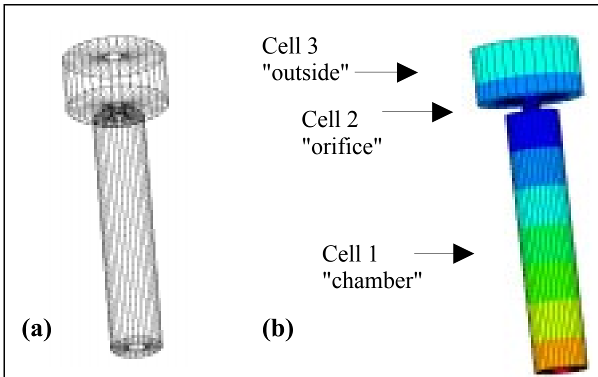

Fig 4. Single-Cell Model of Synthetic Jet (3 domains = 3 cells); (a) geometry; (b) velocity distribution.

At low frequencies, the pressure field inside the cavity is quite uniform. Above 300 Hz we found that acoustic (pressure wave) effects became important and a single cell cavity model would not capture the spatial variation of pressure along the axial direction within the cavity. For high frequency applications, we have proposed a one dimensional model with exactly the same equations as in the one-cell model, but solved on axially arranged polyhedral elements.

3.1 Reduced Models of Synthetic Jets for Aerospace Applications

Aerodynamic control of lifting bodies (aircraft wings, helicopter rotors, missile fins) is becoming important. MEMS technologies are being explored for "smart skins" and for active control. Synthetic jets are a prime candidate for that role [2, 3]. In this section, we demonstrate how synthetic jet arrays could be used for active control of airfoil shape bodies.

A high speed (Ma ≈ 0.2) compressible flow over a NACA-0012 airfoil was simulated concurrently with two rows of synthetic jet arrays placed on top and bottom sections of the airfoil. Each array consists of ten jets which can be individually controlled (Fig. 3). Each synthetic jet cavity is modeled with a compact model consisting of four polyhedral control volumes arranged in 1D mesh. Unlike in the previously reported simulations [2], where jet orifice velocity was prescribed in the sinusoidal harmonic function, the present simulation includes compact models for jet cavities as described above. The simulations have started with steady state flow over the airfoil, followed by unsteady flow with synthetic jets, synchronously actuated. Figure 5 presents the flow pattern over the airfoil with bottom array active. Flow asymmetry, separation and a lift force for zero angle of attack have been observed.

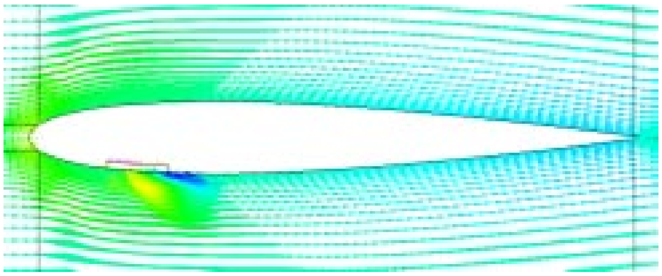

Figure 5. Aerodynamic Simulations of Flow over NACA-12 with Synthetic Jet Array on the Bottom Surface.

In another simulation, a large array of synthetic jets was positioned on an airfoil and demonstrated on active aerodynamic control of lift, drag, stall, and other flow characteristics. This type of simulation enables "virtual flight control" which may be used in the process of design of Micro Air Vehicle (Figure 6).

CONCLUSIONS

The paper presents a novel concept of compact models for synthetic jets. The models use the polyhedra control volume capability of CFD-ACE+ software tool, to model complex dynamic 3D shapes with moving walls and multiple inlets/outlets, using a single cell "super element". The model has been validated against 3D high-fidelity simulation data obtained for a range of parameters such as geometry, actuation frequency, amplitude, operational pressure, etc. High-fidelity models were compared successfully with experimental results from Georgia Tech.

Substantial computational savings are achieved when compact models instead of high-fidelity models are used. The paper demonstrated the synthetic jet arrays simulations for two practical applications: aerodynamic control of airfoils and active spot cooling of electronic packages.

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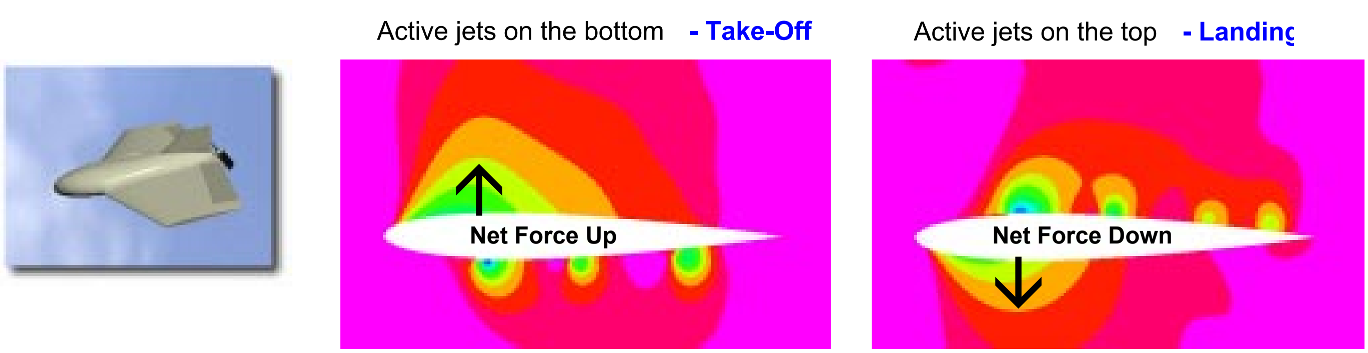

Figure 6. Micro Air Vehicle (MAV), and its virtual flight control, with 3D CFD simulations and reduced models of synthetic jets.