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Estimation of the Flowfield from Surface Pressure Measurements in an Open Cavity

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Introduction

IT is generally accepted that the vortical structures formed in the shear layer above the cavity are convected downstream and interact with the cavity's downstream wall. The interaction sets up a feedback loop that reinforces the development of the vortices in the shear layer causing the cavity to resonate. Although this general description of cavity flow is known, there is still a need for time-resolved information about the shear layer dynamics in order to better understand the feedback process and other noise sources in the shear layer above the cavity. Historically, the large body of work focusing on cavity flows has usually taken one of three forms: evaluation of pressure loads inside of the cavity, evaluation of phase-aligned flow dynamics using optical techniques such as schlieren or particle image velocimetry (PIV) or numerical simulation of Navier–Stokes equations. In cases where the flow dynamics were captured through visual techniques, limitations involved in recording and saving images prevented the technique from yielding time-resolved measurements and coupling them with the surface pressure dynamics. This problem is somewhat overcome in a numerical simulation where time-dependent information can be resolved; however, three-dimensional, time-dependent numerical simulations are quite large, often limiting the Reynolds number and typically requiring a large amount of computing resources. For a more detailed survey of the literature on cavity flows one should refer to many papers on the subject, such as Refs. 1–4.

Recent emphasis in resonating cavity research has focused on both active[5–7] and passive[8–11] control. Passive control strategies have resulted in a favorable reduction in pressure loads for design conditions, but they are unable to adapt to off-design conditions and often exhibit adverse effects in those conditions. Therefore, active control is necessary to yield an adaptive control system to address dynamic cavity flow problems. For active control to be successful there is a need for time-resolved information about flowfield dynamics to be implemented with an adaptive control strategy for optimization in a range of flow conditions. Current experimental techniques are limited in their ability to yield time-resolved whole-field measurements. The current effort focuses on producing a low-dimensional, time-dependent description of the flow to be utilized in producing the necessary information for developing an adaptive control scheme.

As a precursor to a large experimental effort to study the dynamics of the shear layer above an open cavity, the present investigation focuses on the evaluation of stochastic estimation for its use in estimating velocities in the shear layer using multiple surface pressure measurements as predictors. Utilizing surface pressure measurements in the stochastic estimation of velocity is a relatively new idea and allows for applications in many practical situations where difficulties arise from placing probes in the flow. Additionally, using a stochastic estimation technique will allow for constructing time-resolved flowfield details that cannot be readily obtained from current experimental techniques. A multipoint method was recently employed for studying a backward-facing ramp by Taylor,[12] and single-point pressure estimation has been more thoroughly detailed by Naguib et al.[13] The present work utilizes the large eddy simulations of a Mach 1.5 freestream flow over a cavity, with a length-to-depth ratio (L/D) of 6, to extend these earlier formulations for multiple pressure measurements in both linear and quadratic estimates of the flow over an open cavity. Utilizing the data set from time-resolved simulations, one can directly examine the time dependence of the estimated velocity field by comparing snapshots of the flowfield in addition to the statistical properties, which are typically used, to evaluate the effectiveness of linear and nonlinear applications of stochastic estimation.

Stochastic Estimation

Stochastic estimation was presented by Adrian[14] in 1975 as a means of estimating coherent structures in turbulent flows. Later, Cole et al.[15] showed that by utilizing the instantaneous velocity as the condition the time dependence of the velocity field could be estimated. As shown by Picard and Delville,[16] Taylor,[12] and Naguib et al.,[13] this conditional average can be formulated using the wall pressure event as the condition:

$$\tilde{u}_{ijx}(t) = \langle u_{ijx}(t) | P(t) \rangle \tag{1}$$

The subscripts are used to denote the position i and j (two-dimensional flow) and the component x of the velocity that is of interest. Angle brackets denote ensemble averaging, and the velocities and pressures represent only the fluctuating components.

The conditional average can be estimated by a power series as shown by Guezennec[17]:

$$\tilde{u}_{ijx}(t) = A_{ijxk} P_k(t) + B_{ijxlm} P_l(t) P_m(t) + C_{ijxpqr} P_p(t) P_q(t) P_r(t) + \cdots \tag{2}$$

The summation convention has been utilized, and the sum is taken from 1 to K, where K is the number of estimating events (surface pressure measurements in this case). The coefficients are found by minimizing the mean square error of the estimate depending on where the estimate is truncated.

To evaluate the success of the estimate, both the linear stochastic estimate (LSE) and quadratic stochastic estimate (QSE) expansions were formulated for multiple predictors and evaluated for their performance. The formulation of the multipoint estimates for the LSE using either velocity or pressure can be found in many places, and so we will detail only the formulation for the quadratic estimation. The quadratic estimate involves the first two terms of Eq. (2):

$$\tilde{u}_{ijx}(t) = A'_{ijxk} P_k(t) + B_{ijxlm} P_l(t) P_m(t) \tag{3}$$

Note the prime above the linear coefficients in Eq. (3). Owing to the calculation of the coefficients, the linear and quadratic coefficients are not independent, and so the coefficients for the linear term in the quadratic estimate are slightly different from the coefficients in the linear estimate.

Presented as Paper 2002-2866 at the AIAA 32nd Fluid Dynamics Conference, St. Louis, MO, 24–26 June 2002; received 29 July 2002; revision received 19 December 2002; accepted for publication 19 December 2002.

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The process of minimizing the mean square error involves taking its derivative with respect to both A' and B. Setting both derivatives to zero results in two sets of equations that include both A' and B. As long as the temporal separation is zero for all of the correlations, then some of the resulting equations become linearly dependent, which reduces the number of equations from K^2 to $K + (K-1) + \cdots + 1$ because no single combination of subscripts needs to be repeated. Note that this is a special case only for zero-time-lag correlations. The end result can be put in a matrix form to solve for the quadratic estimation coefficients A' and B:

$$[C]_{ijx} = [P]^{-1}[V]_{ijx} \tag{4}$$

where C is a vector containing the estimation coefficients, V contains the velocity-pressure correlations, and P is the pressure–pressure correlations. A more detailed explanation can be found in Murray and Ukeiley.[18]

Results

The data from a large eddy simulation of Mach 1.5 flow over an open cavity were used to evaluate the effectiveness of the LSE and QSE. This data set was generated using the CRAFT code[19] and has been validated against experimental data and empirical relationships in Sinha et al.[20]

One of the keys to the success of stochastic estimation is the strength of the correlation between the estimated quantity and the predictor. If the correlation is low, then the estimation will have significant error. Although not shown in this Note, examination of the correlation between the surface pressure and the velocity field was used to guide the placement of the estimator locations. Extensive studies of the effects of the location for the estimators were conducted, and it was determined that multiple evenly spaced locations along the bottom wall of the cavity yielded the most accurate estimations.

Figure 1 shows the estimated rms velocity field based on an even distribution of 10 points throughout the cavity for both linear and

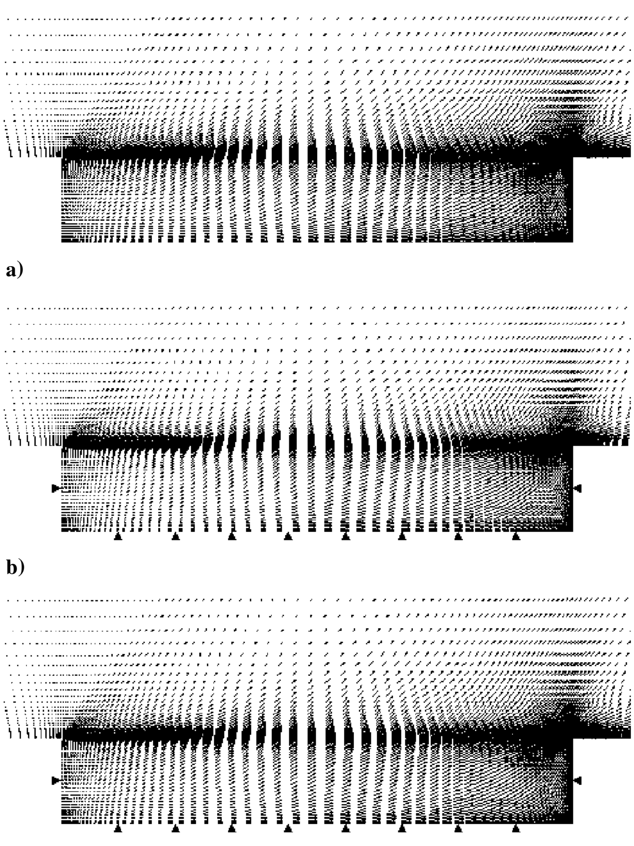

Fig. 1 RMS vector plots: a) simulation data, b) 10-point linear estimate, and c) 10-point quadratic estimate.

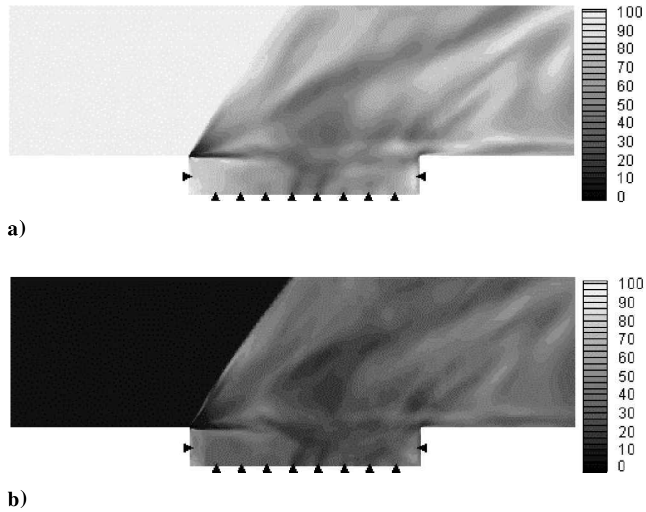

Fig. 2 Percent energy deficit: a) linear estimate and b) quadratic estimate.

quadratic estimation formulations. The estimator locations are highlighted with the triangles along the cavity surface. As stated earlier, this uniform distribution of estimators was observed to yield the best results. Inspection of the difference between the quadratic and linear estimates in Fig. 1 illustrates the fact that the linear part of the estimate captures the bulk of the flow information. Still, overall vector lengths do exhibit a slight increase in the quadratic estimate.

To get a more quantitative idea of the quality of the estimation, the rms values were used to calculate streamwise and normal components of turbulent kinetic energy per unit mass for the fluctuating velocities $[E = \frac{1}{2}(u^2 + v^2)]$. Figure 2 shows the percent deficit in the energy for the linear and quadratic 10-point estimates as compared to that of the simulated data set. In Fig. 2, an energy deficit of 100% (white color) means that the estimate was unsuccessful at representing the energy in the flow. There is a sharp contrast between the quadratic and linear estimate, especially upstream of the cavity's leading edge. This shows that the linear estimate is unable to properly represent the integral properties of the flow, especially far away from the estimator location, which is consistent with the results of Naguib et al.[13]

The method of evaluating the rms values of the turbulent velocity gives a good indication of the completeness of the estimate, but it fails to show whether the estimate can yield the correct temporal dynamics that will allow for evaluation of the time-dependent sources in the shear layer. To evaluate the ability of the estimate to produce time-dependent results, the spanwise vorticity was evaluated and compared to the simulation data for successive time steps ($1e$–4 s between time steps). Figure 3 shows seven consecutive realizations of the spanwise vorticity for the Navier–Stokes simulation, the 10-point linear estimate, and the 10-point quadratic estimate. Figure 3 shows the increase in detail gained by including the quadratic term in the estimate. The linear estimate leaves the large structures rather smoothed out. In contrast, the quadratic estimate is better able to represent the changes in the vortex structures. After examining animations of all 192 available time steps, the linear estimate tends to look like a stationary structure that changes shape, whereas the quadratic estimate is able to show the convection and rotation of the structures over time, showing the quadratic estimate to be more capable of detailing the evolution of the spanwise vorticity.

The greater detail observed in the quadratic estimate likely stems from the coupling of the pressure measurements in the estimate. The linear estimate is simply a weighted sum of the chosen pressure measurements to produce the estimated velocity. The quadratic estimate includes a weighted two-point correlation between the chosen pressure measurements. The flowfield does not affect individual pressure measurements in an independent fashion, and so the inclusion of this "coupling" term between pressure measurements produces an expected improvement and is likely the cause of the enhanced clarity in the quadratic estimated vorticity.

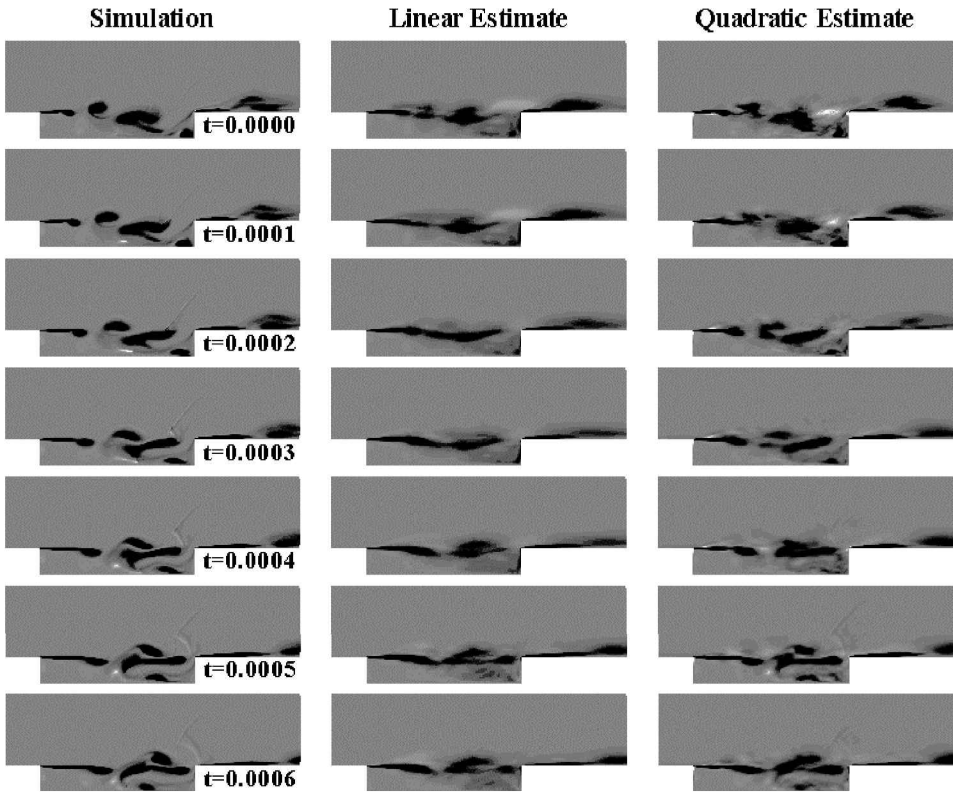

Fig. 3 Spanwise vorticity for consecutive flow snapshots.

Conclusions

Multipoint linear and quadratic stochastic estimations were applied to a resonating open cavity flow data set created using a Navier–Stokes simulation of a Mach 1.5 freestream flow over a cavity with a length-to-depth ratio of 6. The estimate was evaluated by comparing the average fluctuating velocity and spanwise vorticity with that obtained from the simulation.

Results show that a linear stochastic estimate is capable of representing the majority of the flowfield. However, the linear estimate is unable to correctly account for the turbulent energy, especially in the boundary layer approaching the cavity where the quadratic estimate shows a vast improvement over the linear estimate in representing the turbulent energy. Evaluation of the spanwise vorticity further demonstrated the ability of the linear estimate to predict the majority of the flow dynamics. However, the quadratic estimate includes the coupling of pressure measurements and therefore adds contrast and is able to more accurately predict the finer details of the vorticity (i.e., the vortical structure in the mixing layer is less blurred).

From these results, stochastic estimation is shown to be capable of estimating flowfield dynamics from surface pressure measurements. On the basis of the evaluation of the turbulent energy and spanwise vorticity, the quadratic estimate is shown to dominate in its ability to correctly estimate flow kinematics and will prove fruitful in future endeavors using experimental data sets of PIV and dynamic surface pressure measurements. Note that the numerical data set of the cavity flow utilized here provides a flow where the pressure disturbances are directly related to the dominant flow structures; however, it is believed that the estimation procedure described here will prove fruitful in less organized flow, such as turbulent boundary layers, or experimental data that contain higher levels of noise.

Acknowledgments

This work was conducted with support from the Air Force Office of Scientific Research under Agreement F49620-01-1-0326. The authors also thank S. Arunajatesan for performing the numerical simulations.

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Control of a Plane Jet by Fluidic Wall Pulsing

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I. Introduction

PULSED injection at a wall constitutes an efficient way to control and manipulate flows. Significant results have been obtained on both external and internal flows. For example, the control of the boundary-layer separation of external flows was investigated by Smith et al.[1] and Béra et al.[2] for cylinders and by Seifert et al.[3] and MacManus and Magill[4] for wings. In both cases control applied at the wall could delay the separation and increase lift. For internal flows Kwong and Dowling[5] and Ben Chiekh et al.[6] showed that such a control can increase the lateral mixing, hence improving the mean pressure recovery in diffusers.

The ability of pulsed injection actuators to control jets was extensively studied by Smith and Glezer,[7,8] who implemented vectoring control of plane freejets. A synthetic jet actuator (i.e., a zero-net-mass-flux injection made of alternate blowing and sucking) was placed adjacent to the exit plane of a primary jet. Flow visualizations and velocity field measurements showed that the primary jet was deviated towards the actuator. In the most recent work[8] the optimized use of a little longitudinal extension of one wall of the synthetic jet led to a deviation angle of nearly 30 deg for a jet centerline velocity of 7 m/s (based on this velocity: $Re_{\text{jet}} \approx 6 \times 10^3$, $c_{\mu\,\text{control}} \approx 0.5$) and 12 deg for a jet centerline velocity of 17 m/s ($Re_{\text{jet}} \approx 14 \times 10^3$, $c_{\mu\,\text{control}} \approx 0.09$).

Pack and Seifert[9] controlled a circular turbulent jet using a short wide-angle diffuser attached to the exit of the jet. High-amplitude, periodic streamwise excitation at the junction between the jet exit and the diffuser inlet enhanced the mixing and provided a jet deflection towards the diffuser wall. The results showed an obvious effect of the diffuser: at $Re_{\text{jet}} \approx 30 \times 10^3$ and for $c_{\mu\,\text{control}} \approx 0.05$, a deflection angle of 8 deg was registered in the presence of a 30-deg diffuser, vs 2 deg without diffuser.

Parekh et al.[10] applied the control to mixing enhancement by using two pulsed injections, one on each side of the jet, either longitudinal or normal to the main flow. Working on circular and plane jets, they showed that different modes of jet excitations are possible. The direct numerical simulations of Freund and Moin[11] pointed out the complexity of the control mechanism, notably in showing the role of both the injection angle and the Strouhal number.

The present work is mainly an extension to the works of both Parekh et al.[10] and Pack and Seifert.[9] A two-dimensional jet was considered, and excitation was applied on both sides of the jet. A streamwise excitation was retained as being more efficient than a cross-stream excitation. A short large-angle diffuser was also added at the jet exit as this significantly amplified the pulsing control introduced in the streamwise direction. All measurements were made using particle image velocimetry (PIV), so that global maps could be obtained for the analysis of the physical phenomenon involved. The measured two-dimensional fields were then either mean averaged or phase averaged with a condition on the control phase.

II. Experimental Setup

A. Wind-Tunnel Facility

Experiments were performed on a jet issuing from a rectangular nozzle (height $h = 3$ cm, span $4h$). The flow was generated by a low-turbulence subsonic wind tunnel ended by a plane contraction of ratio four and a rectangular channel (length $9h$). The mean velocity at the jet exit was $U_0 = 18$ m/s, and the jet Reynolds number was 36×10^3. The jet exit was connected to a symmetrical two-dimensional divergent (angle 2×45 deg, area ratio 4, and therefore outlet height 12 cm). The divergent was opened on a plenum. Perspex walls were used to provide optical access.

B. Wall Pulsed Control

A pair of pulsed injection actuators was positioned at the jet exit, one actuator symmetrically on each wall of the two-dimensional model. For each actuator the injector was a slit, placed just at the beginning of the diffuser wall, just at the corner: Fig. 1 shows details

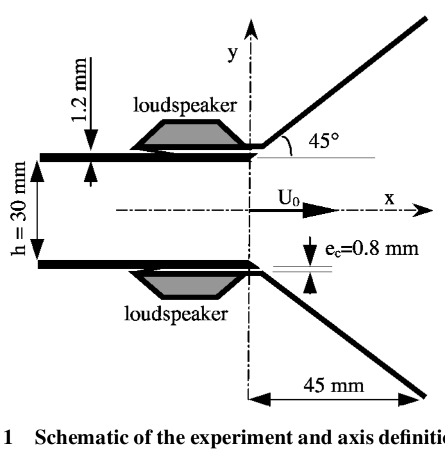

Fig. 1 Schematic of the experiment and axis definitions.

Received 26 March 2002; revision received 23 October 2002; accepted for publication 9 January 2003.

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