Proceedings of FEDSM99
3rd ASME/JSME Joint Fluids Engineering Conference
July 18-23, 1999, San Francisco, California, USA

FEDSM99-7228

COMPUTATION OF SOUND GENERATION AND FLOW/ACOUSTIC INSTABILITIES IN THE FLOW PAST AN OPEN CAVITY

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ABSTRACT

The modes of oscillation and radiated acoustic fields of compressible flows over open cavities are investigated computationally. The compressible Navier-Stokes equations are solved directly (no turbulence model) for two dimensional open cavities with laminar boundary layers upstream. The computational domain is large enough to directly resolve a portion of the radiated acoustic field. The results show a bifurcation from a shear layer mode, for shorter cavities and lower Mach numbers, to a wake mode for longer cavities and higher Mach numbers. The shear layer mode is well characterized by Rossiter modes and these oscillations lead to intense upstream acoustic radiation dominated by a single frequency. The wake mode is characterized instead by a large-scale vortex shedding with Strouhal number nearly independent the Mach number. The vortex shedding causes the boundary layer to periodically separate upstream of the cavity. Acoustic radiation is more intense, with multiple frequencies present. The wake mode oscillation is similar to that reported by Gharib & Roshko (1987) for incompressible cavity flows with laminar upstream boundary layers.

INTRODUCTION

Open cavities on aircraft and other vehicles are subject to intense pressure fluctuations due to flow/acoustic resonance. Resulting internal acoustic loads with sound pressure levels (SPL) in excess of 160 dB have been measured and these can damage stores, fatigue nearby surfaces and components, and lead to intense noise radiation. It has long been known that passive devices, such as spoilers and ramps, can attenuate cavity oscillations under certain conditions. More recently attention has shifted to introducing flow disturbances actively (e.g. Gharib 1987, Vakili & Gauther 1991, Lamp & Chokani 1996, Shaw 1998), as well as closed-loop feedback control (e.g Cattafesta, Garg, Choudhari & Li 1997, Mongeau, Kook & Franchek 1998, Kestens & Nicoud 1998). Feedback control requires a model for the resonant instabilities of the cavity. The cavity resonance is thought to arise from a feedback loop involving (i) shear layer instability and the growth of vortices in the shear layer, (ii) the impingment of the vortices at the downstream edge, and subsequent scattering of acoustic waves, (iii) the transmission of acoustic waves upstream, and (iv) their conversion to vortical fluctuations at the cavity leading edge (receptivity). The first description of this feedback process is credited to Rossiter (1964), who developed a semi-empirical formula to predict the measured resonant frequencies. Later Tam & Block (1978) developed a linear mathematical model to predict the frequencies.

While linear models are effective in predicting the possible frequencies of oscillation, there is as yet no way, for a given set of conditions, to determine the dominant mode of oscillation, the amplitude of oscillation, and nonlinear interactions between modes. Recent experiments by Cattafesta, Kegerise & Jones (1998) have underscored the complicated nonlinear interaction of the different modes, and the possibility of mode-switching. Fabris & Williams (1999) have also recently investigated these issues for low Mach number cavities. The present research is motivated by the need for detailed information about cavity resonance in order to develop robust models which can be used for feedback control laws.

Previous computations of compressible cavity flows have used the two-dimensional unsteady RANS (Reynold's Averaged Navier-Stokes) equations with a $k-\varepsilon$ turbulence model (Lamp & Chokani 1996, Zhang, Rona & Edwards 1998, Fuglsang & Cain 1992). The effectiveness of compressible turbulence models on separated oscillating flows, and especially their radiated acoustic field, remains an open question. Our approach is to use Direct Numerical Simulation (DNS) of two and three-dimensional, low Reynolds number cavity flows to provide an accurate, detailed description of the instability modes, the acoustic sources, and the generated acoustic field. It needs to be stressed that in the context of two-dimensional flows, we use the term "direct" simulation to imply that there is no turbulence model. In this case the flow is an unstable laminar flow which is confined to evolve in only two-dimensions. The turbulent cavity flow is of course three-dimensional, but it is thought that in many cases the resonant modes are approximately two-dimensional. Thus we believe that the two-dimensional calculations will provide valuable data which can be used to develop control laws. Because the acoustic field is also directly resolved in the computations, the resulting database can also be used to investigate the general problem of sound radiation by cavities, including a description of the acoustic sources needed for acoustic analogy theories.

This paper summarizes recent simulations performed at Caltech for unforced two-dimensional simulations. A more detailed treatment of these results will be presented in a forthcoming publication.

COMPUTATIONAL METHOD

DNS of turbulent compressible flows is a challenging and CPU intensive computational problem, especially when radiated acoustic fields need to be directly resolved. Previous DNS studies (Colonius, Lele & Moin,1997, 1994,Mitchell, Lele & Moin, 1995, Freund, Lele & Moin, 1998) have stressed the need for high fidelity numerical methods for aeroacoustic problems, and studied their application to the sound generated by turbulent shear layers and jets. Of particular importance is the use of high-accuracy numerical methods with very low numerical dissipation and nonreflecting boundary conditions. To this end, a sixth order compact finite difference scheme (Lele 1992) is employed for spatial derivatives, and the equations of continuity, momentum, and energy for a compressible perfect gas are integrated with an explicit 4th order Runge-Kutta scheme. The computational domain is made large enough to accommodate 1 to 2 wavelengths of the radiated acoustic field.

Flows with resonance (and globally unstable flows in general) present further difficulties to traditional numerical methods where numerical artifacts can lead to self-forcing of the flow in a process indistinguishable from the physical instability (e.g. Colonius, Lele & Moin 1993). In order to eliminate such effects and to compute the acoustic field accurately, highly accurate non-reflecting boundary conditions are used. We rely on the one-dimensional characteristic boundary conditions formulated by Poinsot & Lele (1992), together with the so-called "buffer zone" technique where fluctuations are artificially damped in a region near inflow/outflow computational boundaries (Colonius et al. 1993, Freund 1997). While these techniques are not as accurate as high-order nonreflecting boundary conditions for linear problems (e.g. Rowley & Colonius 1999), they are more effective in situations where large amplitude (nonlinear) fluctuations must exit the domain. For oscillating flows, it is of critical importance that the boundary locations be determined by careful examination of simulations on different sized computational domains, so that it is assured that the boundary conditions are not responsible for the oscillations.

A schematic diagram of the cavity configuration and computational domain are shown in Figure 1. The upstream laminar Blasius boundary layer is specified along the inflow of the computational domain, and is characterized by its projected momentum thickness, θ (assuming laminar growth), at the cavity leading edge. The Reynolds number is based on the freestream velocity, U, θ , and the kinematic viscosity in the ambient flow, ν. The Mach number of the freestream is M, and the cavity geometry is specified by its length relative to the momentum thickness, L/θ, and its ratio of length to depth, L/D . The wall temperature is held constant and equal to the freestream value, and the Prandtl number is 0.7. For simplicity, the fluid properties are held constant since there are no imposed temperature gradients. Computations are performed in parallel on 8 to 32 nodes of an IBM SP computer. Typical resolutions are roughly 100 points per unit length of cavity. The computational domain extends to roughly $5D$ and $7D$ upstream and downstream of the cavity leading and trailing edges, respectively, and about $9D$ in the normal direction above the cavity. A nonuniform grid, which clusters node points in the boundary/shear layer region, the cavity bottom, and cavity edges, was used. Grid convergence and boundary locations have been studied in detail. The boundary locations referred to above were sufficiently far from the cavity to have negligible effect on the results, and it was also found that roughly 100 nodes per unit length of cavity were needed to assure grid independence. For $L/D = 2$, this results in roughly 400,000 nodes.

RESULTS

Modes of Oscillation

A series of two-dimensional computations have been carried out with varying M, L/θ , and L/D . The computations revealed an interesting bifurcation in the mode of oscillation of the cavity. As the cavity length is increased, relative to the upstream boundary layer thickness (holding depth constant), the

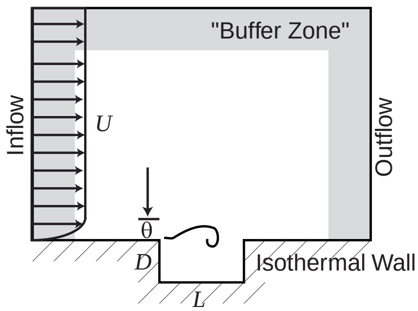

Figure 1. Schematic diagram of cavity configuration and computational domain.

oscillations change character from a "shear layer" mode, for the shorter cavities to a "wake mode" for the longer cavities. The terminology is borrowed from Gharib (1987), who noted a similar bifurcation for incompressible cavity flows.

The shear layer mode is characterized by the roll-up of vortices in the shear layer which impinge on the downstream boundary. The frequencies, as discussed in the next section, agree with those predicted by the Rossiter equation, and consist primarily of Rossiter modes 1 and 2. There is also a relatively weak vortex in the downstream portion of the cavity, and some interaction between the shear layer and the flow in the cavity. Figure 2 shows a snapshot of the vorticity field at a particular phase of the cycle, for L/θ = 53, L/D =2, and $M = 0.6$.

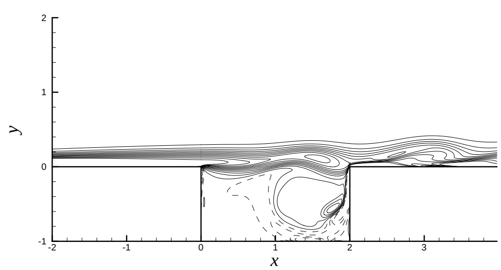

Figure 2. Instantaneous vorticity contours at an instant during the oscillation cycle (shear layer mode). 15 contours between $\frac{\omega D}{U}$ = -5 and 1.67. Positive contours are dashed. L/θ = 53, L/D = 2, $M = 0.6$, Re_θ= 60. Only a small portion of the computational domain near the cavity is shown.

The wake mode is characterized by a large scale shedding from the cavity leading edge, in a manner similar to wake flows. The shed vortex has dimensions of nearly the cavity size, and as it is forming, boundary layer fluid is directed into the cavity. The vortex is shed from the leading edge and ejected from the cavity in a very violent event. The vortex is large enough to cause flow separation upstream of the cavity during its formation, and again in the boundary layer downstream of the cavity as it convects away. Figure 3 shows two snapshots of the vorticity field at particular phases of the cycle for L/θ = 102, L/D =4, and $M = 0.6$.

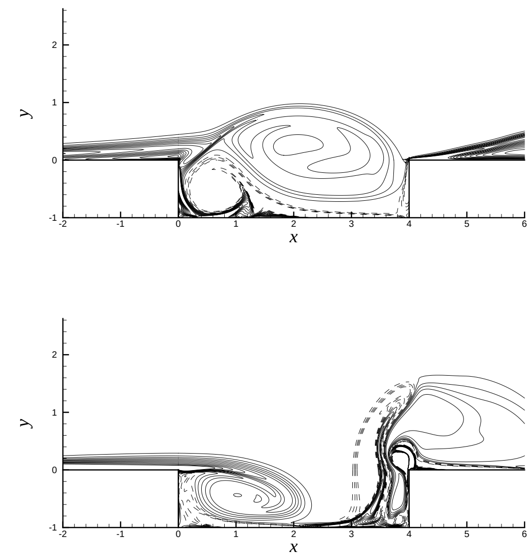

Figure 3. Instantaneous vorticity contours at two different times i during the oscillation cycle (wake mode). 15 contours between $\frac{\omega D}{U}$ = -5 and 1.67. Positive contours are dashed. L/θ = 102, L/D = 4, $M = 0.6$, Re_θ= 60.

Time traces of the normal velocity at $y = 0$ and $x = 0.75L$ are show in figure 4, for runs where L/θ was varied, with constant depth, $M = 0.6$, and $Re_\theta \approx 60$. It is evident that the bifurcation from wake mode to shear layer mode occurs around $L/\theta = 75$. For $L/\theta = 25$, the oscillations are damped and the flow becomes steady. For $L/\theta = 75$, it appears that there is mode switching, with wake and shear layer modes being present at different times. The bifurcation is also a function of M, and for $L/\theta = 102$, shear layer mode exists for $M < 0.3$ and wake mode for $M > 0.3$. Again, time traces for flows near the bifurcation indicated the presence of mode switching.

It is interesting to compare these results with those for the incompressible cavity (an annular gap in an axisymmetric body in water) studied by Gharib & Roshko (1987). In their experiments, where the upstream boundary layer was also laminar, transition between non-oscillatory, shear layer, and wake modes occurred at $L/\theta = 80$ and $L/\theta = 160$. Our data shows that the change

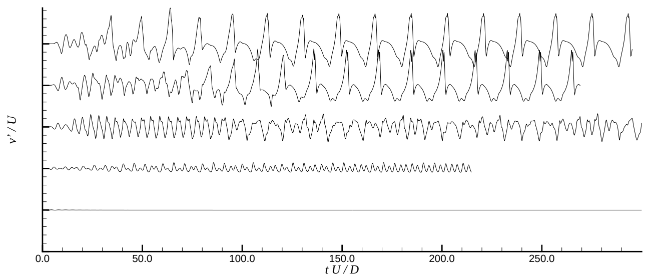

Figure 4. Time traces of the normal velocity, relative to U, at $y = 0$, $x = 0.75L$ for various L/θ. From top to bottom, $L/\theta = 123$, $L/\theta = 102$, $L/\theta = 75$, $L/\theta = 53$, and $L/\theta = 20.3$. The vertical axes have been artificially shifted to show all the data clearly, with major tick marks representing 1 unit. In all cases, $M = 0.6$, $\mathrm{Re}_\theta \approx 60$.

from wake mode to shear layer mode depends also on the Mach number, and further runs are planned to investigate the value of bifurcation in L/θ for lower M. Gharib & Roshko (1987) show that the drag is significantly higher in wake mode (with $C_D = 0.3$ and higher), compared to values around 0.01 to 0.02 for shear layer mode. Similar values are found in the simulations, with an average C_D of 0.008 for $L/\theta = 20.3$, 0.031 for $L/\theta = 75$, and 0.227 for $L/\theta = 102$.

It is not completely clear, at present, what role L/D plays in the bifurcation, though preliminary evidence suggests that it is secondary in importance to L/θ. Two calculations with $L/\theta = 75$, but one for $L/D = 3$ and one for $L/D = 4$, both yielded mode-switching between shear layer and wake mode, and with very similar frequencies and oscillation amplitudes.

The bifurcation could have serious ramifications for the design of active controllers for the cavity that rely on analytical models of the oscillations. The model of Tam & Block (1978), for example, relies on the growth of instability waves in the shear layer, and it would appear that this would only be reliable in shear layer mode. Wake mode appears to be very different, and the data suggest that the wake mode is highly periodic, with a fundamental Strouhal number which is close to Rossiter mode 1, *but which shows much weaker variation with M than do the Rossiter modes*, which, in turn, are only weakly dependent on Mach number for high subsonic values. Furthermore, additional peaks in the spectra are clearly harmonics of the fundamental frequency, in contrast to the higher Rossiter modes which are non-integral. By contrast, computations in the shear layer mode are not periodic, and have peaks in the spectra at non-integral frequencies which appear to correspond closely with Rossiter's mode 1 and mode 2.

It should be noted that the bifurcation from shear layer to wake mode, detected in incompressible experiments and the present compressible computations, appears not to have been noted in previous compressible experiments. The very low Reynolds number of the calculations, and the laminar state of the upstream boundary layer could be the cause of wake mode. For the computations, $\mathrm{R}e_\theta$ is on the order of 100, which is of the same order as the experiments of Gharib & Roshko (1987), but much lower than any compressible experiments. While it is unlikely that the shear layer dynamics are highly dependent on Reynolds number, even for $\mathrm{R}e_\theta$ as low as 100, the impact of the oscillations on an upstream laminar boundary layer could be very different than for a turbulent one. The computations show that in wake mode, the boundary layer alternately separates and reattaches well upstream of the cavity edge, due to the oscillating adverse pressure gradient caused by the vortex shedding. A turbulent boundary layer would be much more resistant to such separation and may preclude the emergence of wake mode. In addition there is the possibility of three-dimensional perturbations to the resonant instabilities. The cavities used in compressible experiments generally have spanwise extent which is not significantly larger than L, which could further enhance three-dimensional aspects of the flow. Clearly more work is needed to definitively resolve the issue.

Acoustic Field

As indicated above, the computations include a portion of the radiated acoustic field. Figure 5 shows instantaneous views of the acoustic field for $M = 0.6$, and two different cavities, $L/\theta = 102$ ($L/D = 4$) and $L/\theta = 53$ ($L/D = 2$). The former is oscillating in wake mode while the latter is in shear layer mode. The acoustic fields are quite different. For shear layer mode, the acoustic field, centered at the downstream cavity edge, is dominated by a single frequency, corresponding to Rossiter mode 2. The most intense radiation occurs at an angle of approximately 145 degrees from the streamwise direction. The acoustic field is intense enough to display nonlinear steepening of the waves– the compressions (dark contours) are steeper than the expansions (light contours). The acoustic field in wake mode is much more complex, and displays a wide range of frequencies. Again, there is intense upstream radiation from the cavity edge, but the wavelength is longer by a factor of about 2, and the amplitude larger by a factor of about 4, compared to the shear layer mode. A very sharp acoustic pulse also emanates from the downstream edge. The origin of this wave is the ejection of the shed vortex from the cavity, depicted in figure 3.

CONCLUSIONS AND FUTURE WORK

Two-dimensional DNS of compressible flow over open cavities reveal an interesting bifurcation in the mode of oscillation of the cavity when the upstream boundary layer is laminar. For shorter cavities, compared to the upstream boundary layer thick-

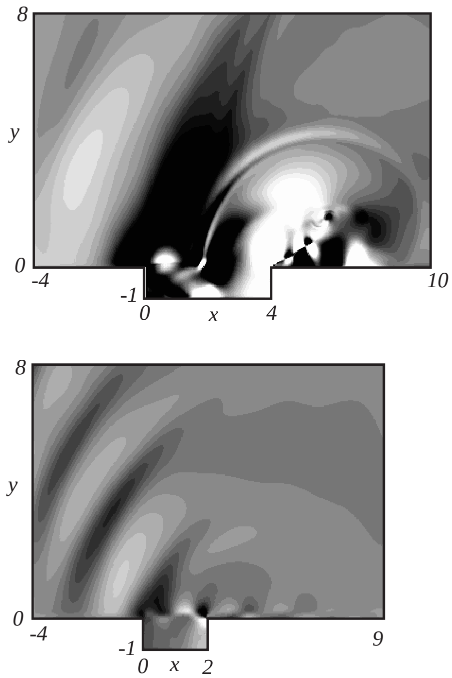

Figure 5. Acoustic field (dilatation) from the DNS. $M = 0.6$, $\mathrm{Re}_\theta = 60$. Top: $L/\theta = 102$ ($L/D = 4$). Bottom: $L/\theta = 53$ ($L/D = 2$). Contours of dilatation are plotted. The entire domain except the buffer region near the boundaries is shown.

ness, and lower Mach numbers the cavity oscillates in a "shear layer" mode, which is consistent with the shear layer instability/acoustic feedback mechanism of Rossiter (1964). The spectra show peaks corresponding to the (non-integral) Rossiter modes 1 and 2. Acoustic radiation is intense and directional, but dominated by a single frequency corresponding to mode 2. For longer cavities, and higher Mach numbers, the cavity oscillations become nearly periodic in time, with one cycle corresponding to the growth, shedding, and ejection of a very large vortex. In this "wake mode", the Strouhal number of the oscillations is nearly independent of Mach number. During growth, the boundary layer fluid is directed into the cavity and the cavity drag is very large. Ejection is accompanied by a sharp acoustic pulse. The vortex is strong enough to cause boundary layer separation both upstream of the cavity, during formation, and downstream of the cavity, after ejection. A similar bifurcation was noted in the incompressible experiments of Gharib & Roshko (1987) (who also had a laminar upstream boundary layer), but has not been seen in compressible experiments at higher Reynolds numbers. We speculate that when the upstream boundary layer is turbulent, the increased resistance to separation upstream of the cavity may be responsible for the discrepancy.

Future work includes (i) further quantification of the modes of oscillation in shear layer mode, and their nonlinear interaction, (ii) determination of the sources of sound for acoustic analogy theories, (iii) three dimensional turbulent simulations, and (iv) simulations of various active control strategies.

ACKNOWLEDGMENT

The authors gratefully acknowledges the support of the National Science Foundation under grant CTS-9501349 and the Air Force Office of Scientific Research under grant F49620-98-1-0095.

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