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Computation of Feedback Aeroacoustic System by the CE/SE Method

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It is well known that due to vortex shedding in high speed flow over cutouts, cavities, and gaps, intense noise may be generated. Strong tonal oscillations occur in a feedback cycle in which the vortices shed from the upstream edge of the cavity convect downstream and impinge on the cavity lip, generating acoustic waves that propagate upstream to excite new vortices. Numerical simulation of such a complicated process requires a scheme that can : (a) resolve acoustic waves with low dispersion and numerical dissipation, (b) handle nonlinear and discontinuous waves (e.g. shocks), and (c) have an effective (near field) non-reflecting boundary condition (NRBC). The new space time conservation element and solution element method, or CE/SE for short, is a numerical method that meets the above requirements [1-4]. A detailed description of the 2-D CE/SE Euler scheme can be found in [1,2], only a brief sketch is given here.

1 The 2-D CE/SE Euler Scheme

Consider a dimensionless conservation form of the 2-D unsteady Euler equations:

$$\mathbf{U}_t + \mathbf{F}_x + \mathbf{G}_y = 0, \tag{1}$$

where the conservative flow variable vector $\mathbf{U}$ and the flux vectors, $\mathbf{F}$ and $\mathbf{G}$, are given in the usual way. In contrast to other schemes, $\mathbf{U}$ and its spatial derivatives $\mathbf{U_x}$ and $\mathbf{U_y}$ are considered as unknowns. Also, the fluxes $\mathbf{F}$ and $\mathbf{G}$ are conveniently written in terms of the components of $\mathbf{U}$. The integral form of Eq. (1) in the space-time 3-D Euclidean Space E_3 is to be solved:

$$\oint_{S(V)} \mathbf{H_m} \cdot \mathbf{dS} = \mathbf{0}, \qquad \mathbf{m} = \mathbf{1, 2, 3, 4}, \tag{2}$$

where $S(V)$ denotes the surface around a volume V in E_3 and $\mathbf{H_m} = (\mathbf{F_m}, \mathbf{G_m}, \mathbf{U_m})$. The time t coordinate points in the direction out from the paper surface. The CE/SE method is naturally adapted to an unstructured grid. The unstructured version of the CE/SE scheme can be briefly depicted by Fig. 1. Here, D, E, F are the triangle centers where the flow data at the previous time step are given. In the space-time E_3 space, (2) is applied to the hexagon cylinder $ADBECF$. $\mathbf{U}$ at the hexagon center at the new time level is first evaluated and then by Taylor expansion, $\mathbf{U}$ at the center O of triangle ABC can be obtained. Surface fluxes along the line segment planes AD, DB, BE, EC, CF, FA (called solution elements or SE's) can be obtained again by Taylor expansions from the 3 centers D, E, and F. In the process, (2) is applied to 3 quadrilateral cylinders $OADB$,$OBEC$ and $OCFA$, which are termed conservation elements ($CE's$).

In the CE/SE scheme, the above flux conservation relation (2) in space-time is the *only* mechanism that transfers information between node points. The conservation element CE is the finite volume to which (2) is to be applied. Discontinuities are allowed to occur in the interior of a conservation element. A solution element SE associated with a grid node (*e.g.*, D, E, F in Fig. 1) is here a set of interface planes in E_3 that passes through this node (*e.g.* DA, DB, EB, EC, *etc.*). The solution variables $\mathbf{U}$, $\mathbf{U_x}$, and $\mathbf{U_y}$ are calculated at this node. Within a given solution element $SE(j,n)$, where j, n are the node index,and time step respectively, the flow variables are not only considered continuous but are also approximated by linear Taylor expansions. Each $S(CE)$ is made up by surface segments belonging to *two* neighboring SE's. The number of equations derived from these flux conservation laws matches the number of unknowns (here 12 scalar unknowns). All the unknowns are solved for based on these relations. No extrapolations (interpolations) across a stencil of cells are needed or allowed.

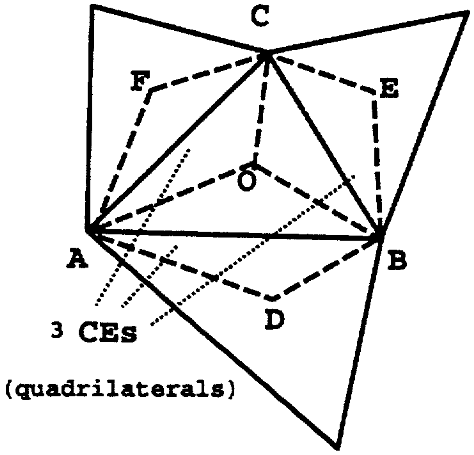

Fig. 1: basic CE/SE grid structure

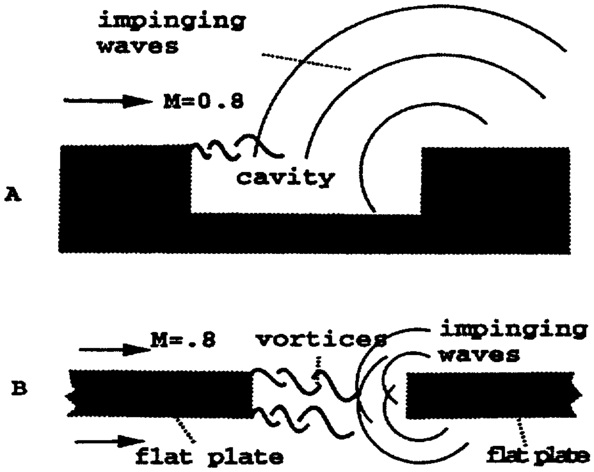

Fig. 2: Sketch of (A) cavity noise, (B) gap noise

For full details of the implementation of the 2-D CE/SE Euler method, leading to the a, $a - \epsilon$ and weighted $a - \epsilon$ schemes, the reader is referred to [3]. The weighted $a - \epsilon$ scheme is used here. ϵ denotes an adjustable parameter that controls the numerical dissipation, and the weighted scheme is intended for cases where discontinuities may be present in the inviscid flow field.

2 the CE/SE Non-Reflecting Boundary Conditions (NRBC)

In the CE/SE scheme, the idea of characteristics stemming from differential equation theory does not properly apply, since we are solving integral equations instead of differential equations. Rather, the following basic criterion is adopted: *In a CE located at the numerical domain boundary, a non-reflecting boundary condition is equivalent to letting the incoming flux from the interior domain to the boundary CE smoothly exit to the exterior of the domain.*

As a matter of fact, the 2-D non-reflecting boundary condition has been proven successful even at the near field boundary. There are various versions of the NRBC. The following are the typical ones employed in our computations. For a grid node (j, n) lying at the domain boundary, the first one, labeled type I, requires that $(\mathbf{U_x})_\mathbf{j}^\mathbf{n} = (\mathbf{U_y})_\mathbf{j}^\mathbf{n} = \mathbf{0}$, while $\mathbf{U}_\mathbf{j}^\mathbf{n}$ is kept fixed at the initially given steady boundary value. Type II, for cases where there is a substantial gradient in, say, the y direction, requires that $(\mathbf{U_x})_\mathbf{j}^\mathbf{n} = \mathbf{0}, \mathbf{U}_\mathbf{j}^\mathbf{n} = \mathbf{U}_{\mathbf{j}'}^{\mathbf{n-1}}, \quad (\mathbf{U_y})_\mathbf{j}^\mathbf{n} = (\mathbf{U_y})_{\mathbf{j}'}^{\mathbf{n-1}}$, where j' denotes the nearest interior node to the boundary node j. The proposed non-reflecting boundary conditions above are all simple, truly multi-dimensional and quite effective. Our experiences show that, in general, the reflection amounts to about 1% or even lower.

3 Numerical results for the gap noise problem

As typical aeroacoustic feedback systems, Figure 2 illustrates the geometric configurations which model the gap and cavity noise problems. Both produce sustainable feedback cycle oscillations as a result of vortex shedding (receptivity) at the upstream edge and acoustic feedback.

Figure 3 shows snapshots of the generation and pairing of vortices and the generation of (nonlinear) acoustic waves by vortex- flat plate impingement in the gap noise problem. The noise generated between the rudder and the stablizer of an aeroplane is a typical example of gap noise. In the current computation, there are 50720 triangle elements for the unstructured mesh in the computational domain. These triangles are actually obtained by dividing a rectangular structured mesh cell into 4 pieces (e.g. Figure 4). The rectangular cell keeps a uniform size of $\Delta x = 0.04$ and $\Delta y = 0.01$ around the area of the gap but grows larger near the boundaries. The mean flow follows the x-direction with Mach number $M = 0.8$. Fig. 3 is taken after 10000 time steps are run. At the inlet, the $M = 0.8$ flow is imposed. At the top and bottom the Type I NRBC is used while at the outflow, the Type II NRBC is specified. The domain shown in Fig. 3 is exactly the the computational domain, no buffer zone is used but still, the CE/SE NRBC is very effective.

4 Numerical results for the subsonic cavity noise problem

In the second problem, a $M = 0.8$ subsonic flow passes over a cavity of aspect ratio 6.5. As in the first problem, tonal oscillations occur in a feedback cycle in

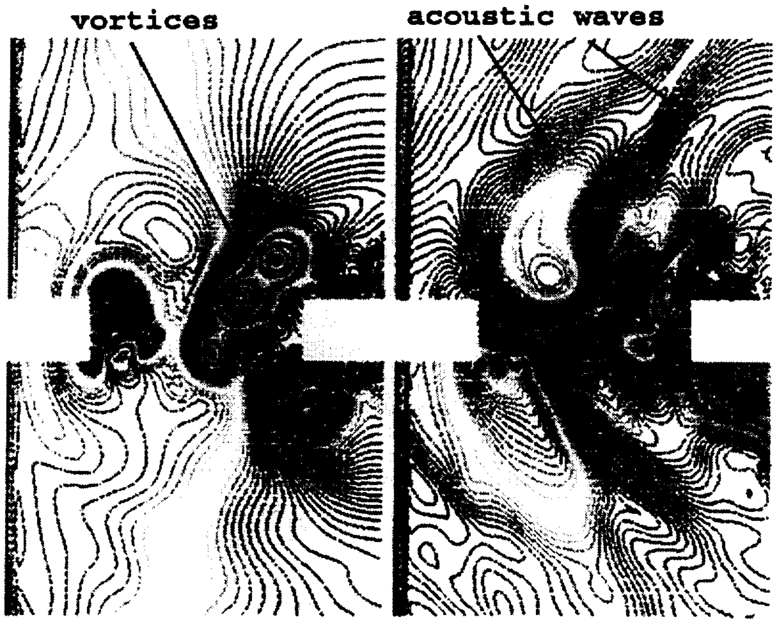

Fig.3: rudder noise; (a) early stage, with vortex shedding and pairing; (b) generation of acoustic waves.

which the vortices shed from the upstream lip of the cavity convect downstream and impinge on the other lip, generating acoustic waves that in turn propagate upstream to excite new vortices.

In the computational domain, 42000 triangular elements are used in the unstructured grid, which is again made from structured rectangular cells (Figure 4). Figure 5 depicts with isobars where the acoustic waves are generated and propagate in a series of snapshots (1-12) in the near field of the cavity. Each snapshot is 3.6 (720 steps) unit apart in time. The boundary conditions are similar to the first example. No visible reflections are observed at the non-reflecting boundaries. At the inflow boundary, upstream propagating waves are well absorbed within a few (4-6) cells, without contaminating the interior domain. From an animation of the solution, the near field acoustic wave structure is quite complicated.

5 Concluding Remarks

Two typical vortex induced, self-excited oscillation aeroacoustic systems are successfully simulated. Through these 'difficult' problems, the capability of the new CE/SE scheme is demonstrated. Specifically,

1. the (2nd order) CE/SE scheme is robust, efficient and yields high resolution, low dispersion results similar to those of higher-order schemes;

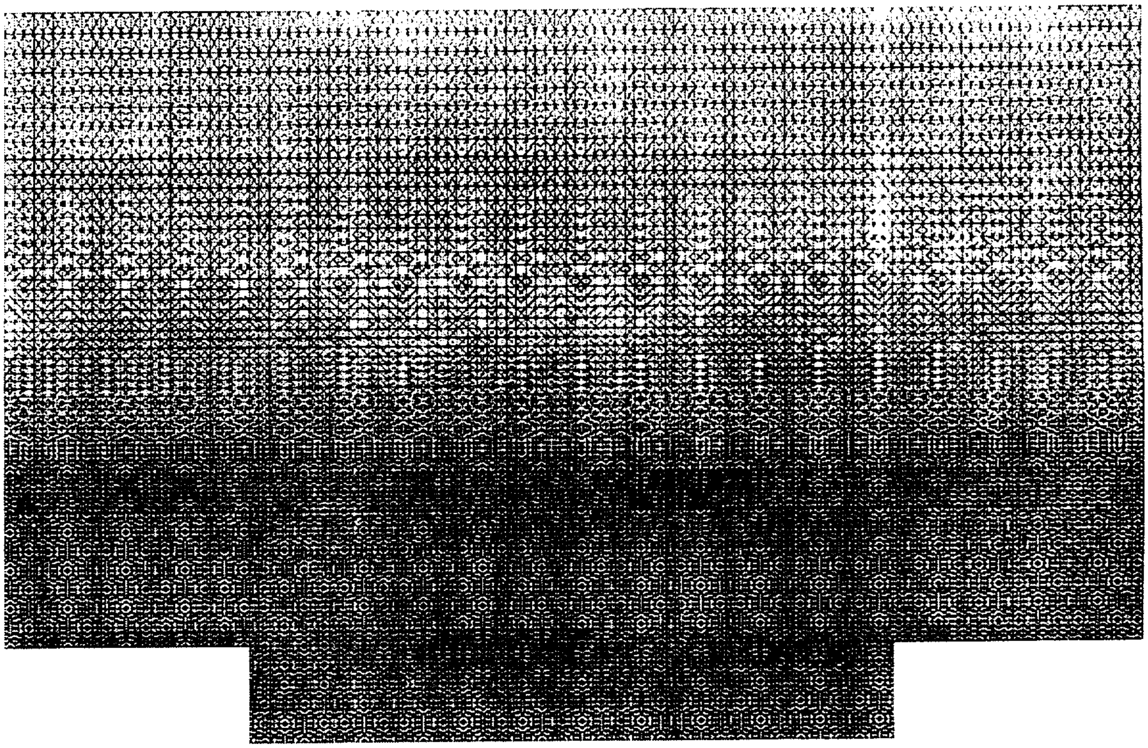

Fig. 4 Unstructured grid used in the cavity noise problem, totally 42000 trianglular elements.

2. the novel non-reflecting boundary conditions based on flux balance is simple, genuinely multi-dimensional, and easy to implement.

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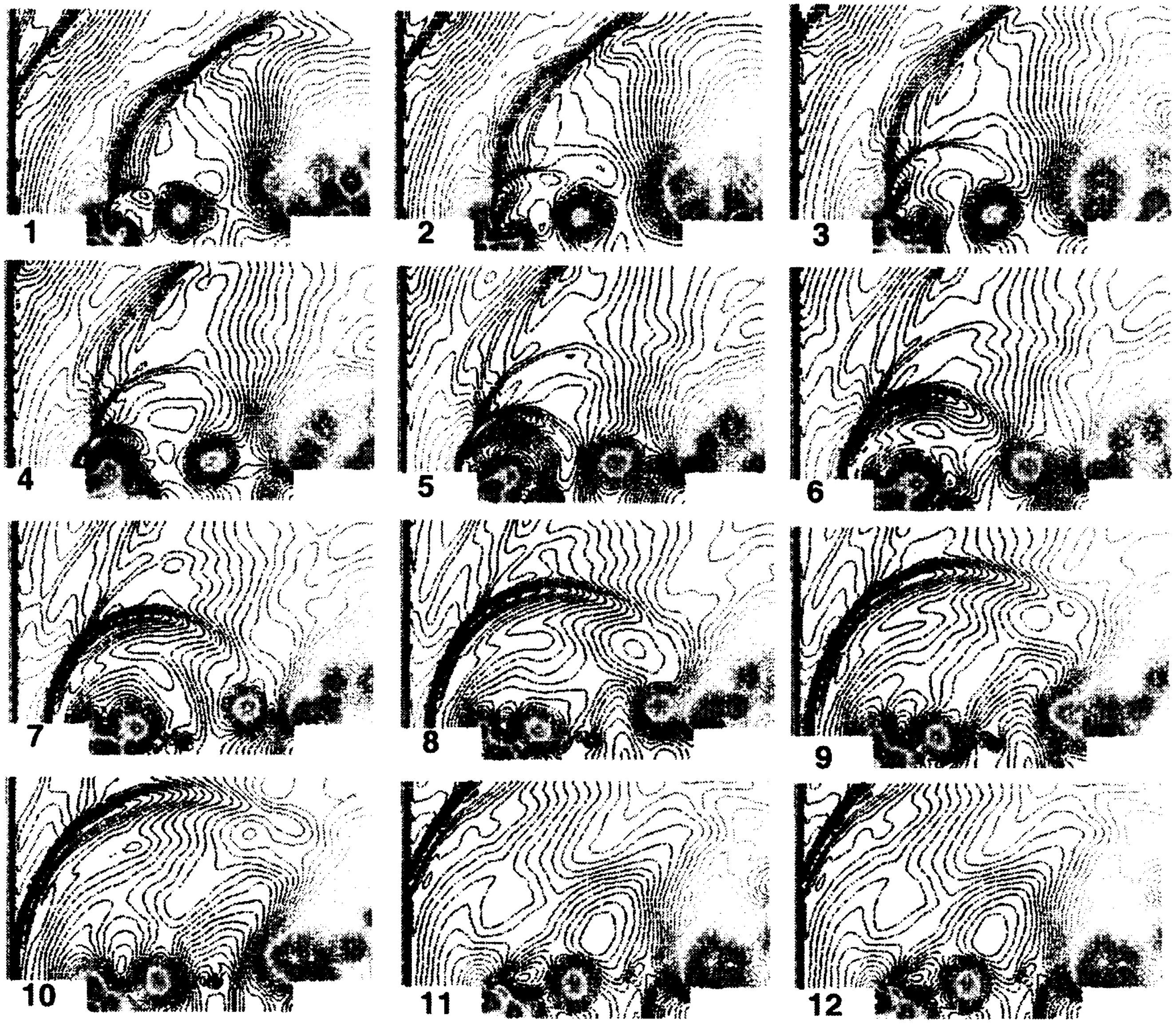

Fig. 5 Isobar snapshots, showing generation of near field non-linear acoustic waves around the cavity.

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