Proceedings of the 12th Asian Congress of Fluid Mechanics
18-21 August 2008, Daejeon, Korea

NUMERICAL ANALYSIS OF AERODYNAMIC NOISE FROM FEEDBACK PHENOMENA USING COMPUTATIONAL AEROACOUSTICS (CAA)

D. J. Lee[*1], I. C. Lee[*2], D. N. Heo[*3] and Y. N. Kim[*4]

[*1] Department of Aerospace Engineering, KAIST, Korea, djlee@kaist.ac.kr
[*2] Department of Mechanical Engineering, KAIST, Korea, essence@kaist.ac.kr
[*3] Innovation Infrastructure & Policy Team, KISTEP, Korea, nyoung@kaist.ac.kr
[*4] Flow-Noise Company, Korea, ynkim@flow-noise.co.kr

ABSTRACT: *Computational Aeroacoustics (CAA) deals about capturing radiated acoustic quantities generated from flow fluctuations numerically. In general, the amplitude of acoustics is less than 4^th order of the flow. Therefore, a higher order scheme, such as compact scheme, is employed to capture the acoustic and flow at the same time. The high order optimized compact schemes are applied in the acoustic from cavity tone and screech tone in the supersonic jet. Cavity tone and Screech tone are generated due to the feedback between flow and acoustic wave. It is recognized that the period is determined by the time required for the flow convection in one direction, the time required for the acoustic propagation in the other direction and the time for phase shift depending on the flows and mode. But the cause of the phase shift and the phenomena of the mechanism have not been clearly explained so far. In this paper, the phenomena are calculated numerically to obtain detail information of flow and acoustic wave to explain the mechanism including the phase shift. Abrupt change in phase of pressure near corner in cavity is observed and is explained. Screech tone is also calculated with the high order high resolution scheme. The tone is due to the feedback between the flow and acoustic and the numerical results are compared with experimental data for the Mach number of mode change, which shows reasonable agreements. Additionally, other effective methods for numerical analysis of feed-back noise of incompressible flow such as whistle noise are addressed and discussed.*

1. INTRODUCTION

This paper focuses on the identification of feedback mechanism between flow and acoustic wave through numerical simulations for various flow speeds and conditions. It is generally known that the flow is excited due to acoustic wave, which wave is generated from the flow fluctuations during the feed back between the flow and wave. However, at a certain condition of flow speed for a given geometry, a resonant occurs between the flow fluctuations and acoustic pressure. Then a pure tone of a single dominant frequency is generated with a significant level of amplitude. The mechanism has been investigated through experiments. Therefore sometimes details of the phenomena are missing in the understanding of the mechanism. In this paper, numerical simulations are conducted for relatively various speeds and conditions to identify the exact phenomena of the feedback mechanism.

First, the flow and acoustic fields are numerically simulated for an open cavity at subsonic flow and screech tone in supersonic jet. In order to analyze the strongly coupled feedback interaction between flow and acoustic wave, nonlinear unsteady compressible Navier-Stokes equations are solved with high-order and high-resolution schemes, which is called Computational Aeroacoustics (CAA). An optimized compact scheme[1] is used. The characteristics of flow and acoustic fields and resonance mode are analyzed under various numerical conditions.

Many researcher have investigated the cavity tone.[2-4] One of them, the Rossiter's equation[2] is frequently used as a standard in evaluating the frequency of cavity resonance. Although the Rossiter's equation can be easily applied to many cases, it cannot provide the frequency without the experimental data. Hence, the feedback mechanism of an open cavity is precisely investigated here and parameters involved are newly defined. To validate these parameters, an integral form of the Rossiter's equation is used. The cross-correlation and the cross-spectral density are used to analyze the characteristics of wave propagation in space and time.

Supersonic jet noise consists of three principal components: turbulent mixing noise, broadband-shock-associated noise, and screech tone[5]. Among three components, the screech tone noise is investigated in this paper. It is interesting that screech tone noise propagates upstream and is produced by a feedback loop near the nozzle exit. For over fifty years, research on screech tone has been conducted via experiments and theoretical equations. Since the 1990s, numerical simulations have been widely used. In this work, the screech tone of an underexpanded jet is numerically calculated with an optimized high order high resolution compact scheme.

Additionally, other effective methods for numerical analysis of feedback noise of incompressible flow such as whistle noise are addressed and discussed.

2. GOVERNING EQUATIONS AND NUMERICAL METHODS

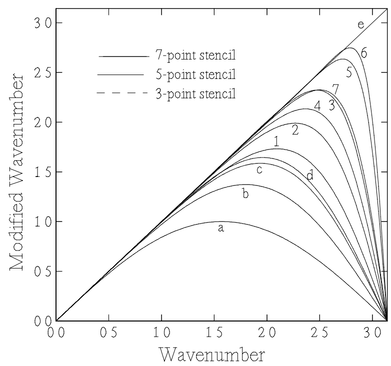
The flux vector form of the Navier-Stokes equations may be expressed as

$$\frac{\partial \boldsymbol{Q}}{\partial t} + \frac{\partial \boldsymbol{E}}{\partial x} + \frac{\partial \boldsymbol{F}}{\partial y} = \boldsymbol{S}_V \tag{1}$$

where **Q** is the vectors of the conservative variables, **E** and **F** are the Euler fluxes, and $\mathbf{S}_V$ is a source term that consists of the viscous flux derivatives. All the components of **Q**, **E**, **F** and $\mathbf{S}_V$ have been fully described in numerous papers and textbooks. If the viscous flux derivatives of right hand side go to zero, the above equations changed to Euler equations. To analyze cavity noise, unsteady compressible Navier-Stokes equations are used. For the case of jet screech tone noise, Euler equations are used.

Generally, the amplitude of acoustics is less than 4^{th} order of the flow. And there exist many methods [5-6] to analyze noise of small amplitude precisely. In this paper one of schemes, optimized high order compact (OHOC) scheme[1], is introduced. These methods are validated in the benchmark problem workshop of CAA.

High-order and high-resolution numerical schemes are applied in a generalized structured grid system to analyze the flow and the acoustic waves. OFOP (optimized fourth-order penta-diagonal) compact scheme is used for evaluating the flux derivatives. The optimized coefficients of OHOC scheme provide the high-order accuracy and the maximum resolution for the central compact schemes. The maximum resolution characteristics of the OHOC schemes are compared with those of other standard central schemes in Figure 1. Combined with high-order finite difference schemes in space, the LDDRK (low dissipation and dispersion Runge-Kutta) scheme is used for integrating the governing equations in time. The adaptive nonlinear artificial dissipation model[7] and generalized characteristic boundary conditions [8]are used to prevent unwanted non-physical results.



a : second-order central differences
b : fourth-order central differences
c : sixth-order central differences
d : Tam's DRP scheme in space
e : exact differentiation
1 : standard Pade' scheme
2 : sixth-order tridiagonal scheme ($c = 0$)
3 : OSOT (optimized sixth-order tridiagonal) scheme
4 : eighth-order tridiagonal scheme
5 : Lele's fourth-order spectral-like pentadiagonal scheme
6 : OFOP (optimized fourth-order pentadiagonal) scheme
7 : tenth-order pentadiagonal scheme

Fig. 1 Maximum resolution characteristics of the OHOC schemes in comparison with the other schemes

3. NUMERICAL SIMULATION OF FEEDBACK TONES

3.1 Mechanism of Cavity Tone at Subsonic Flow

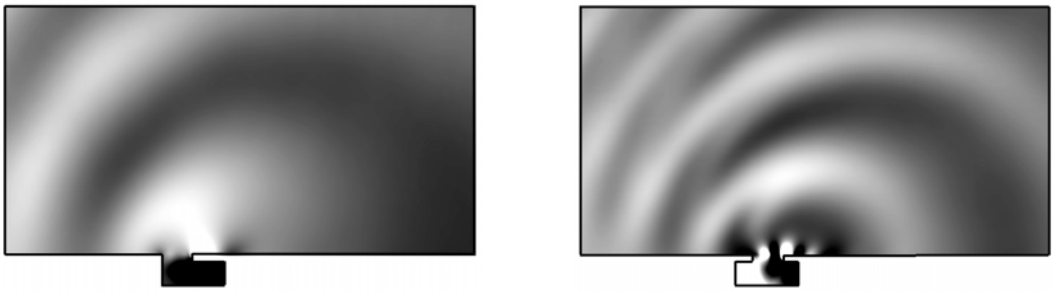
The feedback loop of cavity resonance consists of following steps, as has been well documented in the literature.[2-4] First, a disturbance is produced in the shear layer near the leading edge. The disturbance is amplified as it convects downstream and impinges on the downstream edge. The impingement point becomes an acoustic source point. The acoustic fluctuations generated from this source propagate to the leading edge of the cavity and interact with the free shear layer. If the frequency and the phase of the acoustic energy coincide with the instabilities of the shear layer, resonance can occur. Through these steps, one cycle of a feedback loop is accomplished. Rossiter's equation is

$$\frac{L}{U_c} + \frac{L}{a_\infty} = \frac{n-\beta}{f_n}, \quad n = 1, 2, 3, \cdots \tag{2}$$

$$St_n = \frac{f_n L}{U_\infty} = \frac{n-\beta}{M_\infty + 1/k}, \quad n = 1, 2, 3, \cdots \tag{3}$$

L is the length of the cavity from the leading edge to the downstream edge, U_c is the propagation speed of the vortices, and a_∞ is the free-stream acoustic speed. n is the mode of cavity resonance, and f_n is the frequency of n-th mode. β is the phase lag, which is defined as the phase difference between the vortex and acoustic wave when the vortex impinges on the downstream edge and acoustic waves are generated from the impingement point. $St_n=f_nL/U_\infty$ is the Strouhal number of the n-th mode, U_∞ is the free-stream velocity, and $M_\infty=U_\infty/a_\infty$ is the Mach number of the free-stream. k is a constant defined as the ratio of the vortex propagation speed U_c to the free-stream velocity U_∞, $k=U_c/U_\infty$. It is assumed that the vortex convects downstream at a constant speed U_c, and the acoustic wave propagates upstream at the speed of sound a_∞. β is universally used as 1/4. k varies for each case, because it is determined by fitting Eq. (3) into an experimental result; generally a value of 0.56 is employed.

The flow and acoustic fields of a rectangular open cavity are numerically simulated to investigate the feedback loop of cavity resonance. Fig. 2(a) and 2(b) are the acoustic fields of an open cavity with lids. The opening length is same to D, but the opening position is different. The dominant directions of acoustic propagation are forward-upper for Fig. 2(a) and upper for Fig. 2(b). The frequency of Fig. 2(b) is nearly two times of Fig. 2(a), which means the resonance mode of Fig. 2(a) and Fig. 2(b) are n=1 and n=2 respectively.



(a) Forward open (b) Central open

Fig. 2 Directivity patterns of different opening position (L/D=2, O/D=1, M_∞=0.5, θ/D=0.04 and $Re_\theta=U_\infty\theta/\nu$=200)

When pressure wave **approaches the downstream edge**, it is shown that pressure contours **attached to the forward facing wall inside of cavity**. Because of this phenomenon, the pressure below the downstream edge keeps the same phase as that in front of the downstream edge, and there is no phase shifting inside of cavity. When the **flow passes the downstream edge**, compression effect in pressure field occurs in front of the cavity and secondary vortex is generated behind of cavity. Therefore there is sudden phase shifting by 90 degrees in pressure near the downstream edge outside of cavity. These results support that 0 is adequate for the phase lag when the acoustic source point exists inside the cavity and 1/4 is adequate when the acoustic source point exists outside of the cavity.

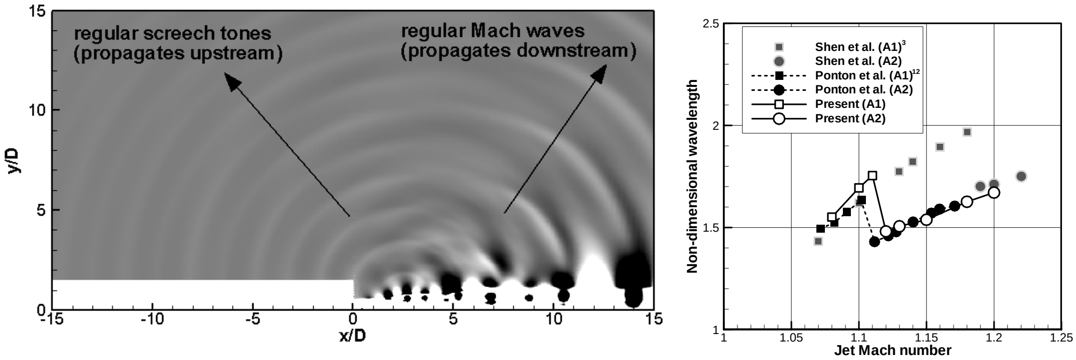
In this paper, newly developed concepts of the feedback mechanism in an open cavity are suggested. They are about effective length and phase lag. Although the mean velocity of vortex convection is about $0.3U_\infty$, the flow speed in front of the vortex generation point near the leading edge is nearly U_∞. The time required for flow to move from the leading edge to the vortex generation point is much smaller than that required for vortex to move from the vortex generation point to the **vortex collapse point**. Thus, the effective length is defined as the distance between the vortex generation point or the leading edge and the vortex collapse point. When a vortex is collapsed, the acoustic wave is generated at the surface of the cavity. The generated acoustic wave propagates forward and excites the shear layer, which induces a vortex directly or the acoustic wave excites the flow on the surface of the leading edge.

$$\int_{VG}^{VC}\left(\frac{1}{u}+\frac{1}{a-u}\right)dl_{\text{(along vortex convection path)}} = \frac{n-\tilde{\beta}}{f_n}, \quad n = 1, 2, 3, \cdots \tag{4}$$

$\tilde{\beta}$ =0 is adequate for rectangular cavity and second mode of cavity with lids like Fig. 2(b). $\tilde{\beta}$ =1/4 is adequate for first mode of cavity with lids like Fig. 2(a). Eq. (4) is compared with the exact frequency obtained directly from the far-field acoustic signal of numerical simulation to validate the accuracy of these concepts.

3.2 Transient Behavior of Screech Tone at Supersonic Flow

Using the numerical algorithm described earlier, we have simulated the screech tone of a supersonic jet numerically. Fig. 3(a) shows the instantaneous pressure contour of a Mach number 1.18 cold jet. From the contour, we observe the Mach wave propagating downstream and the screech tone propagating upstream. **As is well known**, sound waves of screech tones radiate out in a region around the fourth to fifth shock cells downstream of a nozzle exit.



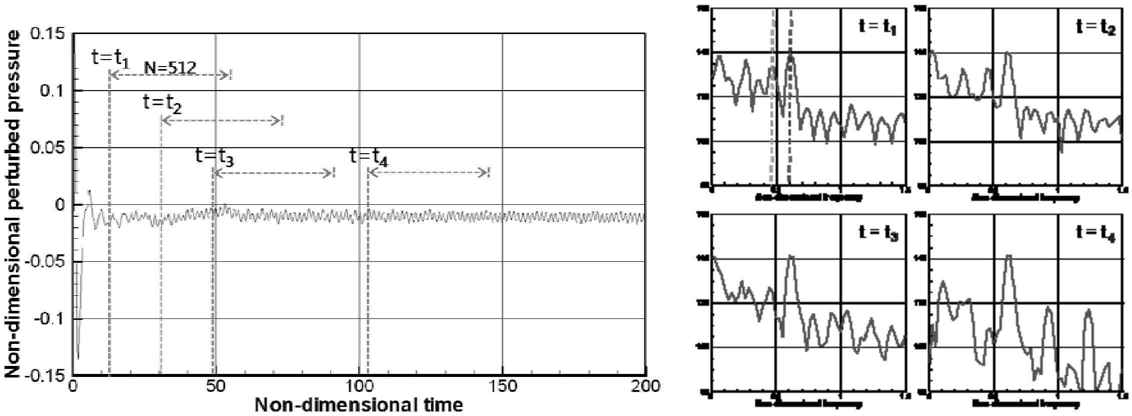
(a) Visualization of noise propagation (b) Wavelength variation

Fig. 3 Visualization of noise propagation ($0.99<\rho/\rho_a<1.01$) of Mach number 1.18 jet and wavelengths of screech tone

The numerical results are compared with both the experimental results of Ponton and Seiner[9] and other numerical results from C.K.W. Tam et al.[10] The numerical results show good agreement with the other results, particularly the experimental results in Fig. 3(b). From experimental data, we observe two axisymmetric screech tone modes, and the mode change occurs in the region of jet Mach number between 1.10 and 1.11. The present numerical simulations show that the axisymmetric mode changes between jet Mach number 1.11 and 1.12.

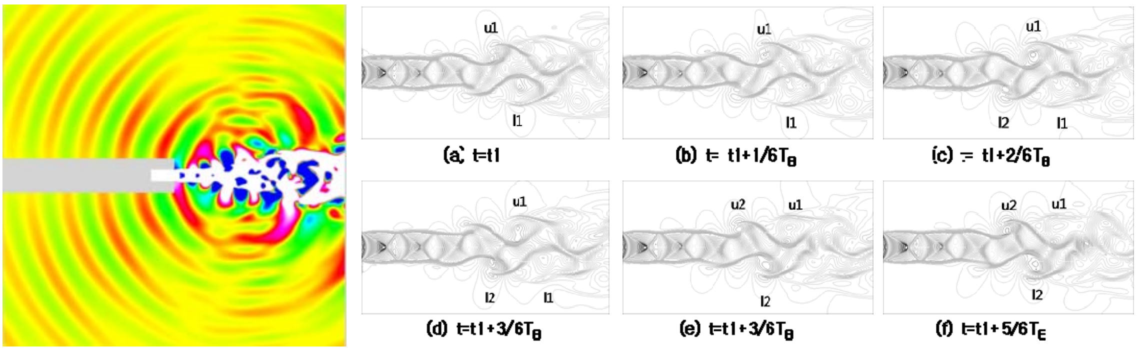
One screech tone component is dominant for a given jet Mach number except at mode change region. However **the largest component** is not so dominant at the initial stage during the formation of the tone. Figure 4 shows a time history of non-dimensional perturbed pressure at one point of nozzle exit plane for jet Mach number 1.18. At the initial stage, the pressure signal is not so stable and some irregular variation is observed. However, the pressure signal becomes stable and the irregular variation also becomes small as non-dimensional time increases. Fast Fourier Transform (FFT) is performed to investigate the characteristics of pressure signal at the early stage. Four non-dimensional times, shown as t1, t2, t3, and t4 in Fig. 4(a), are selected and **512 data are** acquired at each selected time for performing FFT

Figure 4(b) shows various FFT results when jet Mach number is 1.18, which **generates A2 mode**. FFT results at 4 different computational times in the beginnings are shown in Fig. 4(b). Only 512 data are used at each time since component of screech tone is stabilized just a short time after beginning. At the earliest time (t=t1), components of both A1 and A2 modes exist together and their amplitude difference is only about 6 dB. However, the amplitude of A2 component becomes stable and that of A1 component becomes smaller as time increases. It is observed that component of both A1 and A2 modes exist in the beginning and A2 mode becomes dominant as computational time increases for the case of jet Mach number 1.18. Note that the A1 mode can be also observed and dominant **depending on the analysis method** at jet Mach number 1.18 as shown in Fig. 3(b).



(a) Definition of four different time period (b) FFT results at four different time period

Fig. 4 Time history of perturbed pressure at one point of nozzle exit plane and its FFT results for 1.18 jet



(a) Visualization of 3D screech tone (b) Variation of density contours during one period

Fig. 5 Numerical analysis of three dimensional screech tone for 1.43 jet

Additionally, three dimensional screech tone is numerically simulated for 1.43 supersonic jet. Fig. 5(a) shows the visualization of three dimensional screech tone propagation when the jet Mach number is 1.43. It is observed that the screech tone of **upper side and the screech tone of lower side** show half period of 180 degrees phase difference. Fig. 5(b) shows the variations of density contours during one period.

3.3 Whistle Noise at Incompressible Flow

There are many treatments to handle the low speed flow noise problems. Lee & Koo[12] used splitting method for noise prediction of a spinning vortex. It splits the flow and acoustic variables to resolve difficulties in scale disparity, especially for low Mach number flows. Hydrodynamic density concepts[13] are used for the quadrupole noise. Moon & Seo[14] used incompressible CFD (computational fluid dynamics) solver for the flow solver, and perturbed acoustic equation for the noise radiation. It can be applied to complicated noise source problems. A new method for simulating phenomena of flow **feedback** owing to the acoustic pressure is developed by the authors. It uses both acoustic mode analysis and CFD solver.

Fig. 6 and 7 show the results of calculation for the flow locking in whistle geometry. Using this method, we can simulate acoustic flow locking dueto feedback, which is dominant in specific resonance frequency region.

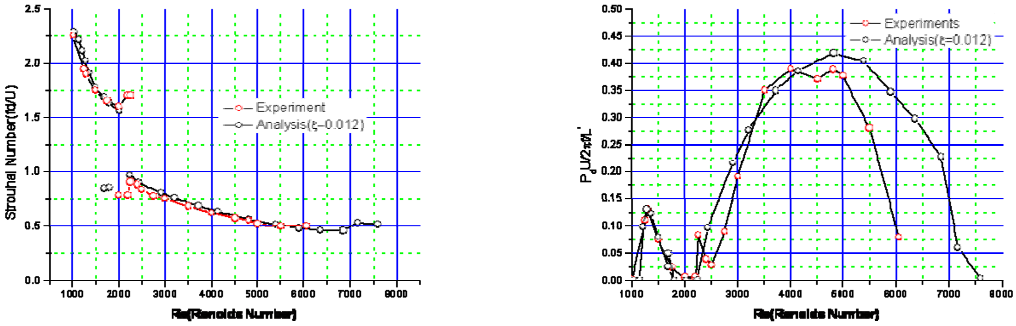
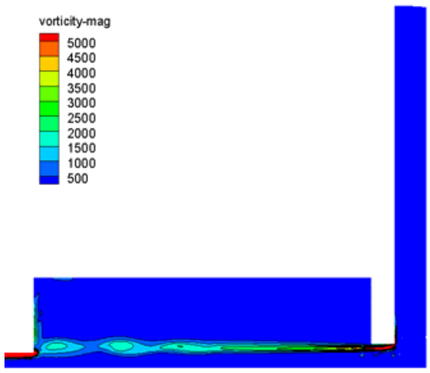
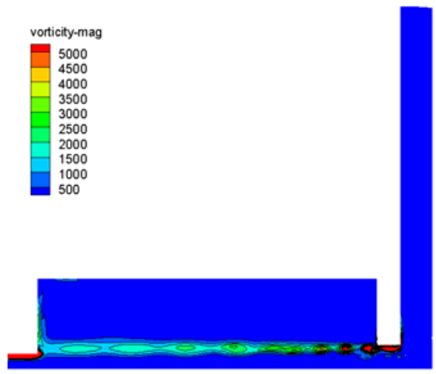


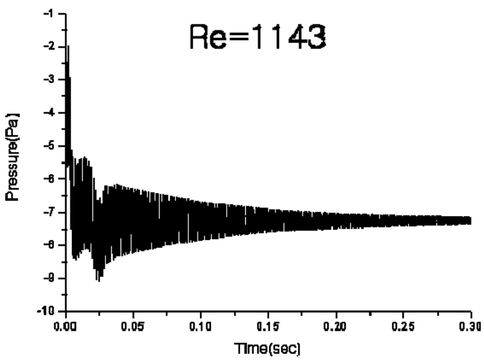
Fig. 6 Flow locking with respect to Reynolds number



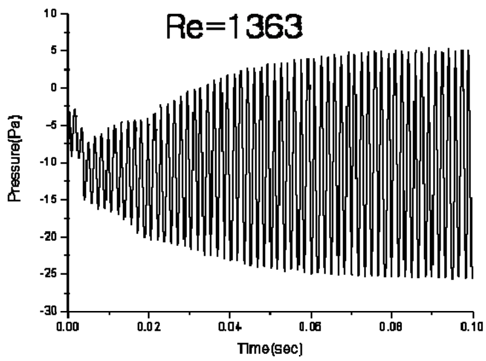
(a) Vorticity contour of unlocked case(Re=1143)



(b) Vorticity contour of locked case(Re=1363)



(c) Pressure history of unlocked case(Re=1143)



(d) Pressure history of locked case(Re=1363)

Fig. 7 Vorticity contour and pressure history of unlocked case and locked case

4. CONCLUSIONS

The high order optimized compact schemes are applied in the acoustic from the cavity tone and screech tone in the supersonic jet. Cavity tone and Screech tone are generated due to the feedback between flow and acoustic wave. It is recognized that the period is determined by the time required for the flow convection in one direction, the time required for the acoustic propagation in the other direction and the time for phase shift depending on the flows and mode. But **the cause of the phase** shift and the phenomena of the mechanism have not been clearly explained so far. Abrupt change in phase of pressure near corner in cavity is observed and is explained. Screech tone is also **calculated with the** high order high resolution scheme. The tone is due to the feedback between **the flow and acoustic** and the numerical results are compared with experimental data for the Mach number of mode change, which shows reasonable agreements and the transient behavior of screech tone is investigated. Additionally, other effective methods for numerical analysis of feedback noise of incompressible flow such as whistle noise are addressed and discussed.

REFERENCES

[1] Kim JW and Lee DJ. Optimized compact finite difference schemes with maximum resolution. *AIAA Journal*, 23(5), 1995, pp. 887-893.
[2] Rossiter JE. Wind-tunnel experiments on the flow over rectangular cavities at subsonic and transonic speeds. Aeronautical Research Council Reports and Memoranda, Technical report 3438, 1964.
[3] Rockwell D. and Naudascher E. Review-Self-sustaining oscillations of flow past cavities,.*Journal of Fluids Engineering*, *Transactions of the ASME*, 100, 1978, pp. 152-165.
[4] Rowley C W. Modeling, simulation, and control of cavity flow oscillations. PhD thesis, California Institute of Technology, 2001.
[5] Tam CKW and Webb J. Dispersion-Relation-Preserving Schemes for Computational Aeroacoustics. *Journal of Computational Physics*, 107, 1993, pp. 262-281.
[6] Lele S. Compact Finite Difference Schemes with Spectral-like Resolution, *Journal of Computational Physics*, 103, 1992, pp. 16-42.
[7] Kim JW and Lee DJ. Implementation of boundary conditions for optimized high-order compact scheme, *Journal of Computational Acoustics*, 5(2), 1997, pp. 177-191.
[8] Kim JW and Lee DJ. Generalized characteristic boundary conditions for computational Aeroacoustics. *AIAA Journal*, 38(11), 2000, pp. 2040-2049.
[9] Ponton MK and Seiner JM. The Effects of Nozzle Exit Lip Thickness on Plume Resonance. *Journal of Sound and Vibration*, Vol. 154, No. 3, 1992, pp.531-549.
[10] Shen H and Tam CKW. Numerical simulation of the generation of axisymmetric mode jet screech tones. *AIAA Journal*, Vol. 36, No. 10, 1998, pp. 1801-1807.
[11] Heo DN, Kim JW and Lee DJ. Study of noise characteristics of an open cavity with cross-correlation analysis. 2003, AIAA paper 2003-3104.
[12] Lee DJ and Koo SO. Numerical study of sound generation due to a spinning vortex pair. *AIAA Journal*, 33(1), 1995, pp. 20-26.
[13] Harding J and Pope D. Sound generated by a stenosis in a pipe, 1990, AIAA paper 90-3919.
[14] Moon Y and Seo J. Accuracy assessment of hydrodynamic/acoustic splitting methods for low Mach number flow, 2003, Proceedings of workshop on flow noise, pp.59-78.