Aeroacoustic Characteristics of Cavity Resonance on Very Low Subsonic Flows

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저아음속 유동에 놓여진 개방형 공동의 공력소음 특성

고성룡, 문영준

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Abstract

The tone generation mechanism and aeroacoustic characteristics have been investigated for flow over open cavities using direct acoustic numerical simulations. Physically the tone generation mechanism of open cavity is more complicated when flow instabilities are excited by the correlation effects of flow parameters. From non-dimensional parameter studies in very low Mach number range, it is shown that characteristics of cavity resonance inherently involve typical acoustic pattern at each discrete tone frequency, and especially in laminar flow the fundamental tone frequency is determined within flow instability criterion of laminar shear layer as well as cavity geometry, length to depth ratio.

1. Introduction

Through many experimental and analytical approaches, it was investigated to reveal the mechanism of fluidic-acoustic oscillation over open cavity, and it is generally known that wave disturbances are produced by the interaction of an oscillating shear layer with the cavity downstream edge.The disturbances then excite the stability of the shear layer at the cavity upstream edge, forming a feedback cycle. The fundamental parameters that determine the mode of cavity oscillations have been known from the earlier investigations. When flow speed is large enough to show feedback mechanism closed by aeroacoustic interaction, the fundamental tone frequency of cavity oscillation follows the famous Rossiter's semi-empirical formular[7], equation (1).

$$St = \frac{m-\gamma}{1/\kappa + M_\infty} \tag{1}$$

where St is the Strouhal number, m is an integer number sequence, κ is the ratio of the vortex convection velocity across the cavity mouth to the freestream velocity, M_∞ is the Mach number of the flow, and γ is an empirical constant determined from the experimental data. Different from the longitudinal feedback mechanism of shallow cavities, the studies about deeper cavities have shown that flow mechanism of generating the intense cavity tones can either be an acoustic resonance such that the aerodynamic characteristics are driven by unsteady pressure fluctuations across cavity opening. According to the numerical results from mathematical cavity model by Tam[8], deep cavity resonance occurs due to flow instability

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rather than by the energy contributions from turbulent broadband noise. Besides these features about flow oscillation mechanism, in a very low Mach number range, the acoustic wave propagating into the far field from the cavity shows a typical shape of monopole source radiation induced by aeroacoustic resonance, and Howe[4] has shown dipole and monopole contribution to aeroacoustic characteristics of cavity resonance. From the analytical solutions using Green's function, near the resonance frequency the combination of monopole and dipole source generates an omni-directional waves with substantial acoustic energy transfer to the normal direction to the cavity, and at the frequencies out of the resonance mode dipole source dominates the wave propagation and its directivity.

Using the Direct Acoustic Numerical Simulation, one of the objectives in the present study is to reveal the relationship between flow instability and normal resonance of deep cavities at low Mach number $M_\infty \leq 0.15$.

2. Numerical method and flow definition

2.1 Numerical method

The Direct acoustic Numerical Simulation has many common tactics with the traditional CFD approaches. Though CAA (Computational Aeroacoustics) needs high-accuracy, low-dissipation methods in the numerical aspects, the system of equations basically follow the main physics of compressible flow. The governing equations are two-dimensional compressible Navier-Stokes equations which are solved for simulating both aerodynamic and acoustic fields. For the purpose of resolving anisotropic turbulent behaviors, a non-linear expression of Reynolds stress model, Explicit Algebraic Stress Model[3], is used in Favre averaged system equations coupled with $k-\epsilon$ two equations model.

The governing equations are integrated in time explicitly with a four-stage Runge-Kutta method and are also spatially discretized with a sixth-order compact finite difference scheme[5]. In practical aspects, application of high order compact scheme to the stretched meshes has numerical instability arising from the numerical truncations or failure of capturing the high wave number phenomena. Therefore, a tenth-order spatial filtering[10] is used for enhancing the numerical stability with high frequency cutoff.

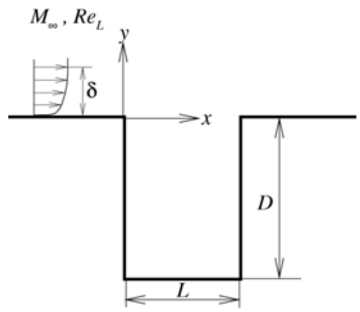
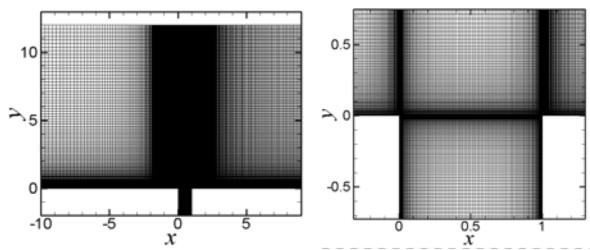


Fig. 1 Schematic view of open cavity.

Figure 1 shows the cavity configuration in a brief sketch in x-y plane, and all the length scales are normalized by the cavity base length(L) in the computation. The freestream Mach number is M_∞ and Reynolds number is Re_L which is fixed at 6,000 for laminar flow simulations and 100,000 for URANS. The incoming boundary layer thickness is δ and the momentum thickness at the origin is θ_0.



(a) Whole view (b) Near cavity mouth

Fig. 2 Computational domain.

For an example, the computational meshes 121×141 are used for the cavity inside and 601×141 for the outside in Fig. 2 (total mesh size : 101602 nodes). The domain size is set to encompass at least one acoustic wavelength, and the buffer zones with a size of $2L$ are used at the inlet and outlet in the x-direction. A uniform velocity profile is imposed at the inlet domain surface. The boundary layer coming from cavity upstream is developed with no-slip adiabatic wall boundary condition. To avoid undesirable spurious waves from farfield, two non-reflecting boundary treatments are applied. a buffer zone treatment[2] is used for the inflow and outflow domain edges where the acoustic and vorticity waves convect across the domain edges, whereas the upper far-field edge is treated with local one-dimensional inviscid relations[6] with a damping zone.

2.2 Normal mode

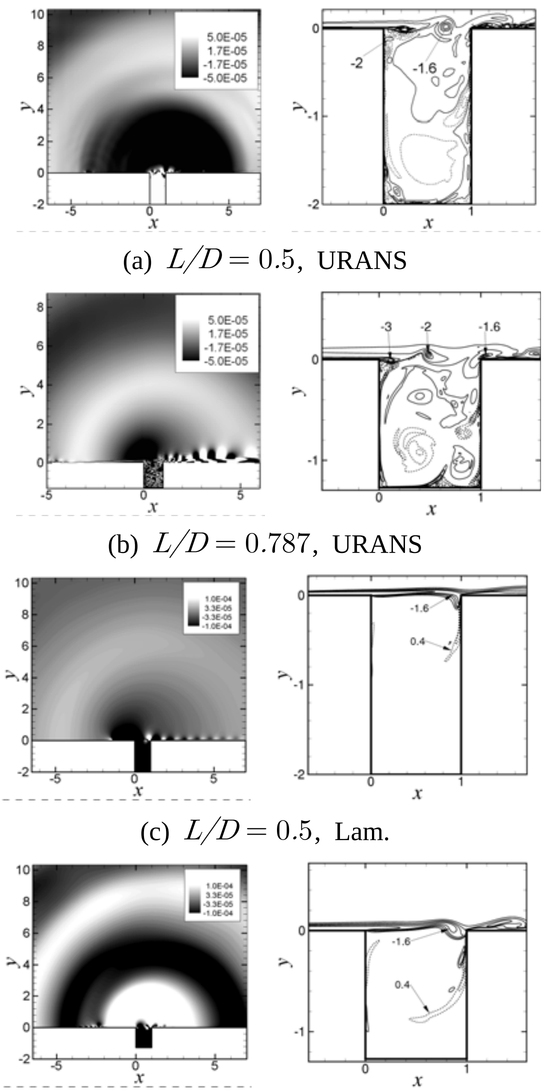
In the present study the two earlier studies[1,9] about normal mode mechanism in low speed flow are considered as reference, and basically two different geometries are used through out the simulations : cavity length to depth ratio $L/D = 0.5$ and $L/D = 0.787$. As indicated in Table 1, flow speeds are not same with each other.

Table 1 Fundamental frequencies of normal resonance.

	M_∞	L/D	L/θ_0	St
EXP.	0.093[1]	0.5	81	**0.91**
	0.095[9]	0.787	100	**1.4**
TUR.	0.1	0.5	100	1.0
CAL.	0.1	0.787	100	1.4
LAM.	0.15	0.5	100	0.4
CAL.	0.15	0.787	100	1.0

Since there is no clear flow oscillation in $L/D = 0.5$ cavity with laminar flow condition at $M_\infty = 0.1$, freestream Mach number $M_\infty = 0.15$ is considered with the concept of focusing our regard to normal resonance mechanism. Normal resonance can be characterized aerodynamically as flow oscillation like Helmholtz resonator at very low Mach number and acoustically monopole source radiation. As shown in Fig. 3 the solutions of the present simulations, qualitatively are satisfying the above aeroacoustic features. However as written in Table 1 the laminar simulations did not match well with experimental data quantitatively.

The first motivation of present investigation is what makes difference between turbulent and laminar flow simulation of normal resonance. According to Tam[8], normal resonance is acoustic radiation damping mechanism and there is no exception whether flow is laminar or turbulent, because “zero flow condition” was assumed in his study.



(a) $L/D = 0.5$, URANS

(b) $L/D = 0.787$, URANS

(c) $L/D = 0.5$, Lam.

(d) $L/D = 0.787$, Lam.

Fig. 3 Dilatation and vorticity contours of turbulent and laminar flow over cavities.

Then the discrepancy between the experimental data and present simulation results may come from hydraulic conditions of turbulent and laminar boundary layer though corresponding momentum thicknesses are artificially set to a same value. For the purpose of looking into physical differences of normal resonance in laminar flow in detail, some selected simulation conditions are tested as listed in Table 2. The results of RUNS L5T1 and L7T1 are already shown in the laminar cases of Fig. 3

Table 2 Simulation parameters.

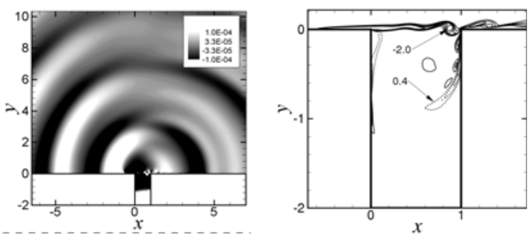
RUNS	L/D	L/θ_0	M_∞	St
L5T1	0.5	100	0.15	0.4
L5T2	0.5	150	0.15	1.2
L7T1	0.787	100	0.15	1.0
L7T2	0.787	150	0.15	1.1
L7M1	0.787	100	0.03	1.12
L7M2	0.787	100	0.05	1.13
L7M3	0.787	100	0.075	1.15
L7M4	0.787	100	0.1	1.12

In Table 2 fundamental tone frequencies are also introduced taken from the numerical solutions.

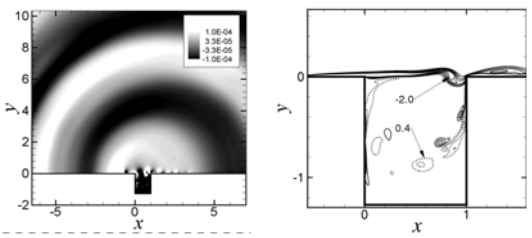
3. Result

3.1 Geometry and shear layer thickness

In the first place since the two laminar cases in previous section are emitted lower tone frequencies, the thinner momentum thickness $L/\theta_0 = 150$ is used without change any other parameters.



(a) $L/D = 0.5$, L5T2



(b) $L/D = 0.787$, L7T2

Fig. 4 Dilatation and vorticity contours for different flow parameters at $M_\infty = 0.15$.

As shown in Fig. 4, however, the results are very different from the expectation such that one is shows dipole source radiation and the other does not change the acoustic mode. Comparing L5T2 with L5T1 ($L/\theta_0 = 100$ case), vortex shedding at shear layer in L5T2 is clearly observed. At farfield region, acoustic waves propagate like dipole source radiation and there exist radiation null region in direction normal to the cavity.

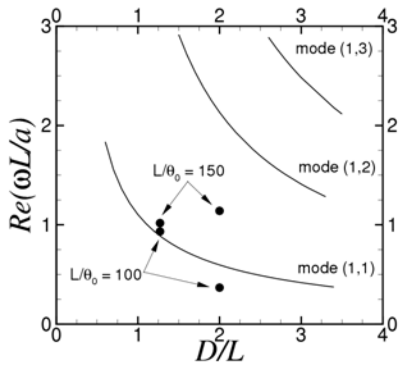


Fig. 5 Tone frequencies at given boundary layer thickness for different L/D with $M_\infty = 0.15$: solid lines ; theoretical prediction[8].

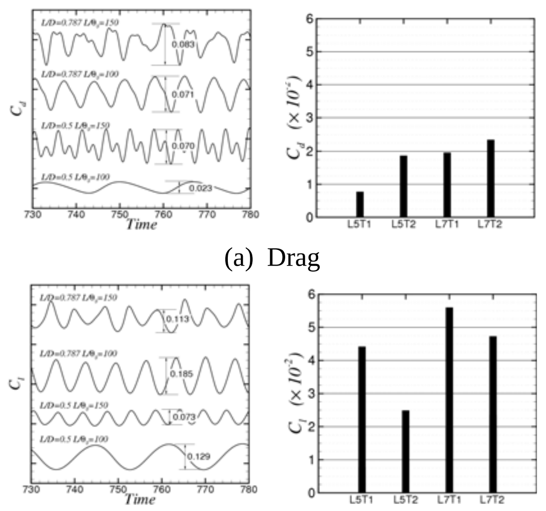
These results agree with the acoustic radiation damping proposed by Tam. As shown in Fig. 5, three cases, L5T1, L7T1 and L7T2, show qualitatively resemblance to the theoretical prediction of fundamental tone frequencies. The deviation from normal resonance only occurs at the case L5T2 by changing the shear layer thickness L/θ_0. The tone generation mechanism of L5T2 is different from the acoustic radiation damping. In this case the free shear layer has less relation with acoustic resonance, but is associated with the frequency of spatial instabilities in the shear layer. From the theoretical analysis about the Orr-Sommerfeld equation, free shear layer is unstable to disturbance wave number of magnitude,

$$\frac{\omega\delta}{c_r} = 0.42 \tag{2}$$

where ω is and c_r is speed of wave passing at a fixed point of observation. When the shear layer has the hyperbolic tangential velocity profile, the frequency where the disturbances are convected downstream from the shear layer is taken from equation (2) as

$$\frac{f\theta}{U_\infty} = 0.017 \qquad (3)$$

The Strouhal number of L5T2 case is 1.2 and, from equation (3) the corresponding momentum thickness of free shear layer is about $L/\theta = 70$ which is physically consistent with the computational result of the shear layer thickness at cavity opening.



(a) Drag

(b) Lift

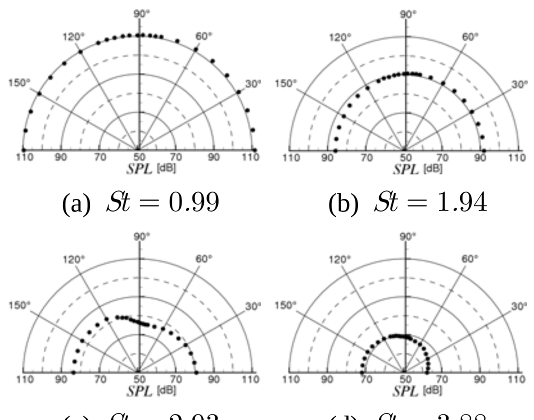
Fig. 6 Drag and lift coefficients.

In order to comparing the sensitiveness to flow parameter variation, root-mean-square values of drag and lift coefficients are presented in Fig. 6. The most clear tendency is that in deeper cavity $L/D = 0.5$ the change of shear layer thickness can influence the susceptible flow oscillation. In other words, As cavity depth become shallower, shear layer spanning the cavity mouth is excited by pressure disturbances reflected from cavity bottom wall.

Drag forces exerted inside cavity range comparable for all cases except the L5T1 cavity in Fig. 6(a). A portion of flow disturbances produced at the downstream edge of cavity transfer to upstream direction, and are associated with drag forces. On the contrary, lift forces are closely related with normal resonance. As shown in Fig. 6(b), the cases in normal mode resonance have large values of lift force coefficient. It is the evidence of normal mode mechanism influenced by correlation of cavity geometry and flow instabilities as in the mathematical model by Tam[8]. aerodynamic behavior of shear layer is correlated with flow instability that wave reflections from bottom wall act as an onset of self-sustained aeroacoustic mechanism.

3.2 Compressibility

Another acoustic peculiarity in laminar flow can be understood by differing freestream Mach number. As already known from Table 2 the fundamental tone frequencies do not follow the typical normal resonance behavior. The Strouhal numbers are nearly fixed at a mode though freestream speed decreases from $M_\infty = 0.15$ to $M_\infty = 0.03$, and aerodynamically the shapes of shear layer oscillation also show a similar pattern. Instead of following normal resonance behavior, freestream Mach number influences the acoustic wave radiation to be turn from monopole into dipole.

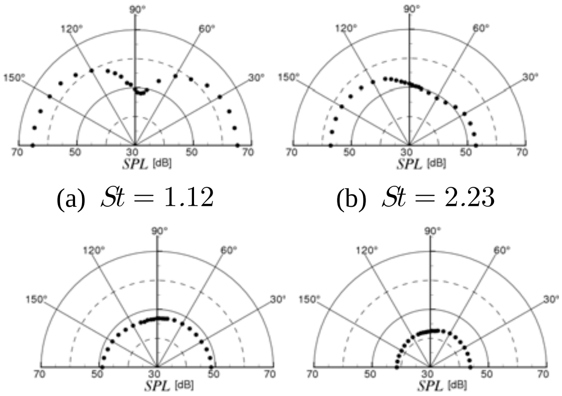


(a) $St = 0.99$ (b) $St = 1.94$

(c) $St = 2.93$ (d) $St = 3.88$

Fig. 7 Acoustic directivities at different tone frequencies of $M_\infty = 0.15$ case.

Acoustic wave directivity at $M_\infty = 0.15$ is shown In Fig. 7. Since the fundamental tone, Fig. 7(a), is located near normal resonance frequency, the primary acoustic radiation is monopole. As studied by Howe[4], the range of monopole frequency has order of 1 at near $M_\infty = 0.1$, and becomes very higher as decreasing freestream velocity.



(a) $St = 1.12$ (b) $St = 2.23$

(c) $St = 3.35$ (d) $St = 4.47$

Fig. 8 Acoustic directivities at different tone frequencies of $M_\infty = 0.03$ case.

As freestream Mach number decreases to very low speed $M_\infty = 0.03$, primary wave propagation is a dipole in Fig. 8, not a monopole observed in higher Mach numbers range $M_\infty > 0.1$. This result agrees with the solution of algebraic model. When the cavity tone frequencies are far deviated from the cavity resonance, the radiation directivity also is inverted into isolated dipole shape, and in the direction normal to the cavity wall there is null radiation. The cavity tone frequencies at low speed flow, $M_\infty < 0.2$, are presented in Fig. 9. For the cavities over laminar flow the fundamental tone frequencies do not follow the normal resonance curve, and monopole source radiations are observed at each fundamental tone frequency or at higher frequencies with a tendency of typical normal mode behavior.

4. Conclusion

In the present numerical study, normal resonance mechanism in turbulent and laminar flow oscillation over open cavities is to be understand with direct acoustic numerical simulations. Caused by the physical differences of vortex formation between turbulent and laminar shear layer, normal resonance at very low speed flow can be maintained in the turbulent flow by following the mathematical theory and the experimental data. Instead of showing normal resonance behavior, the laminar flow oscillation behaves sensitively within the bound of flow instability.

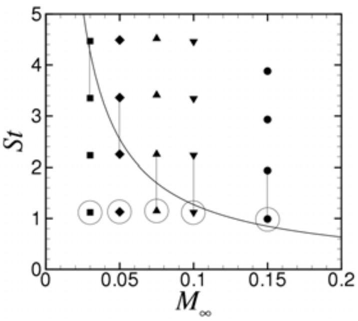


Fig. 9 Tone frequencies at different Mach numbers : large hollow circles ; primary frequency, solid lines between harmonics ; monopole dominant frequencies, solid curve ; theoretical prediction[8].

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